Laboratory Investigation of Methods to Reduce Channel Degradation

MRD Hydraulic Laboratory Series Report No. 17

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Presented in this report are results of a model study in which methods to reduce channel degradation were investigated. The model studies were conducted during the period July 1979 to April 1980 at the Mead Hydraulics laboratory. Channel degradation occurs when the amount of sediment leaving a river reach is greater than the amount entering that reach. Depending upon the magnitude of the degradation, it may have numerous adverse impacts on man and the environment. Channel degradation can: leave water supply intakes for powerplants and municipal water systems high and dry, undermine bridge foundations, expose pipeline crossings, render ineffective bank stabilization works, increase farmland erosion, degrade water quality, lower the adjacent water table thereby depleting ground water reserves, wetlands, & lakes.

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DEPARTMENT OF THE ARMY

CORPS OF ENGINEERS

LABORATORY INVESTIGATION OF METHODS TO REDUCE CHANNEL DEGRADATION

CONDUCTED AT

MEAD HYDRAULIC LABORATORY

MEAD, NEBRASKA

U.S. ARMY ENGINEER DISTRICT; OMAHA

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I. INTRODUCTION

1. **General.** Presented in this report are results of a model study in which methods to reduce channel degradation were investigated. The model studies were conducted during the period July 1979 to April 1980 at the Mead Hydraulic Laboratory near Mead, Nebraska, by personnel of the Hydraulics Section of the Omaha District Corps of Engineers, Messrs. Eugene Matson, William Howard, and Roy Singleton. The model study was reviewed and guidance provided by the following: The Technical Engineering Branch of the Missouri River Division, Messrs. Alfred Harrison, Warren Mellema, and George Patenode; the Kansas City District, Messrs. Walter Linder and Thomas Burke; and the Omaha District, Messrs. Howard Christian, Kenneth Murnan, Jack Mielke, Vern Horihan, and Frank Vovk.

2. **The Degradation Problem.** Channel degradation occurs when the amount of sediment leaving a river reach is greater than the amount entering that reach. Depending upon the magnitude of the degradation, it may have numerous adverse impacts on man and the environment. Channel degradation can: leave water supply intakes for powerplants and municipal water systems high and dry; undermine bridge foundations, expose pipeline crossings; render ineffective bank stabilization works; increase farmland erosion; degrade water quality; lower the adjacent water table thereby depleting ground water reserves, wetlands, and lakes. Tributaries to the degrading stream would also be subject to degradation thereby greatly multiplying the overall problem.

3. Channel degradation may not always be undesirable. Channel degradation downstream from a hydroelectric plant could add benefits because of the increase in potential energy. In flood-prone areas, channel degradation could reduce the incidence of flooding, and in agricultural areas it could improve interior drainage.

4. **Study Reach.** For this study, a reach of the Missouri River between River Mile (RM) 712 and RM 720 was chosen. See Plate 1. This reach is part of a larger reach from Sioux City to Omaha which since closure of the main stem dams on the Missouri River and with construction of the Bank Stabilization and Navigation Project has experienced degradation. See Plate 2. In the study reach since 1952, there has been from 5 to 8 feet of degradation and an additional 1 to 3 feet of degradation is projected to occur by the year 2000.[6] The study reach includes part of Omadi Bend, all of Browers and Snyders Bends, and part of Glovers Point Bend. See Plate 1 and Photo 8. The concave banks of these four bends are protected with continuous stone fill revetment. A segment of the convex bank in Snyders Bend as well as the convex bank of Glovers Point Bend is also revetted, limiting the maximum channel width in these zones to approximately 700 feet. Dikes protruding from the banks and spaced at various increments varying from 500 feet to 1,000 feet are used along the convex bank in all of the bends to constrict the channel width at these points to approximately 600 feet. Three dikes in

[6] Numbers refer to references listed in Appendix A.

Browers Bend and 11 dikes in the portion of Glovers Point Bend included in the model have sloping end sills. The end sills extend normal to the flow and riverward from the dike structures about 100 feet, further restricting the channel.

5. **Purpose of Study.** The purpose of the study was to investigate methods which possibly could be used to prevent channel degradation. Since degradation occurs as a result of more sediment leaving a river reach than enters, the methods investigated were proposed because it was believed they would reduce the sediment transport rate either by reducing the velocity or turbulence of the stream. The methods investigated in this study include:

a. Reducing the riverward length of the dike structures thereby increasing the effective channel area and reducing the channel velocity.

b. Decreasing the number of river training structures which protrude into and disrupt the flow.

c. Constructing cross channel grade control sills to fix the bed elevation at the sill location and reduce the upstream channel bed velocities.

6. **Constraints.** The study reach is within the Bank Stabilization and Navigation Project of the Missouri River and consequently there are certain design features which cannot be changed. The navigation depth of 9 feet at the design discharge (30,000 c.f.s.) must not be compromised nor can the number of river training structures be decreased such that control of the river would be lost through thalweg meandering. The project should also be able to function with no adverse effects from the degradation controls for flows up to the summer high flow (60,000 c.f.s.).

II. THE MODEL

7. **Model Scales.** Generally, in movable bed models the distortion between the horizontal scale and the vertical scale is four or less, although a maximum distortion of six is permissible.1/ In this study it was decided that the model should contain two complete bend ways so that if any of the methods investigated caused a loss of control of the river it could be observed. Subsequently, physical restraints necessitated the construction of the model with a horizontal scale of 1:300 and a vertical scale of 1:52.

8. **Vertical and Horizontal Control.** All structure heights on the Missouri River are referenced to a construction reference plane (CRP) defined as the flow profile for the summer discharge which is exceeded 75 percent of the time. In this stretch of the river, the summer discharge is 30,000 c.f.s. and the CRP slope is about 0.000197. The 1976 hydrographic survey 4/ (see Plate 5) along with construction completion reports 5/ were used in determining the bed elevations and locating and constructing the structures in the model. See Photo 1. Determination of the model structure elevations was based on a model CRP slope of 0.0006 for the 30,000 c.f.s. flow simulated in the model. For comparative purposes the thalweg profile for a 30,000

c.f.s. model condition (Run 48, Plate 6) has been superimposed on the prototype thalweg profile on Plate 5. As may be seen, the thalweg profiles and the contour patterns of the model and prototype compare favorably.

9. **Model Construction.** Concrete blocks were used to outline the model channel. See Photo 2. All structures were formed from sheet metal with a textured rubber carpet padding glued to the surface to simulate the prototype stone roughness. The sheet metal structures were placed on or adjacent to the concrete block walls. See Photos 2, 3, 4, 5, and 6. Water surface monitoring devices were located on 10-foot centers through the model. See Photo 3. Four-inch diameter tile pipes were placed across the model entrance to aid in controlling the flow distribution. See Photo 4. A settling basin was provided adjacent to the model entrance so that the recirculated sediment could be removed. In this way the model was "starved" of sediment and subsequently the channel degraded. See Photo 5 and Plate 7. Provisions were made so that the structures could easily be modified to change the channel width. See Photo 6. The channel and bank areas were backfilled with finely ground walnut shells, mean diameter of 0.3 mm and specific gravity of 1.3, to simulate the Missouri River bed material. See Photos 5, 6, 7, and 8. In the tests using grade control sills (GCS), the sills were constructed of a crushed limestone with mean diameter of 6 mm. This material was carefully placed into the model at the specified locations to form structures of a triangular cross section with uniform crest at 10 feet below the 30,000 c.f.s. flow profile. See Photo 7. The depth of 10 feet was chosen to ensure a navigation depth of 9 feet. Since these structures were constructed of loose stone, the crests tended to degrade during the tests as a result of settling and/or high velocities. They were always brought back to grade before beginning the next test.

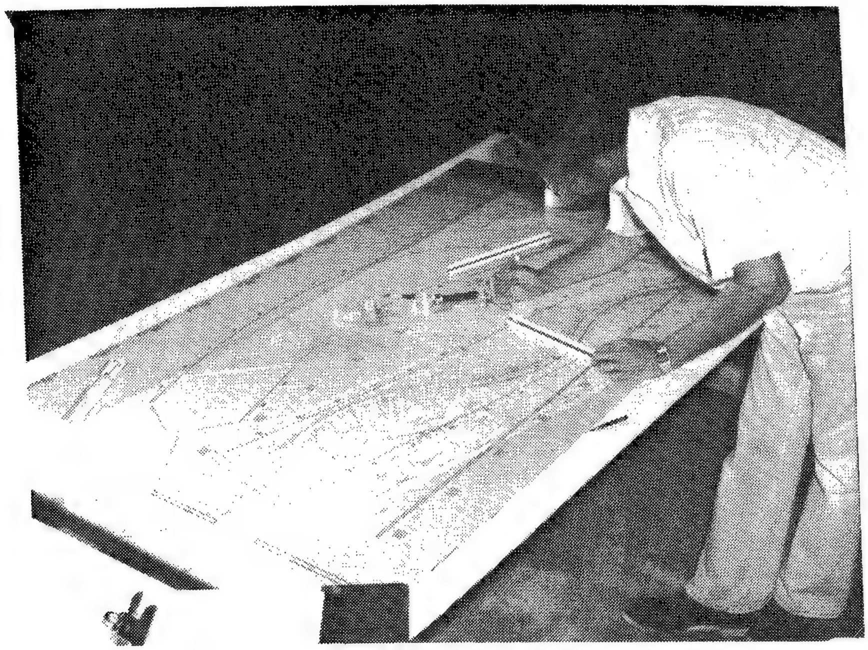
III. OPERATING PROCEDURES*

10. **Stage Control vs. Slope Control.** Generally, in model studies at the Mead Facility the water surface elevation or stage at the mid-point of the model is held constant. Also, all sediment transported out of the model is recirculated with the water to the upper end of the model. Therefore, if the stage is held constant, a change in discharge (velocity) would produce a corresponding change in depth (the average bed elevation would remain constant because all sediment is recirculated). In this study, it was not desirable to hold the water surface elevation at the mid-point constant because the average bed elevation and consequently the average velocity would be affected by the following:

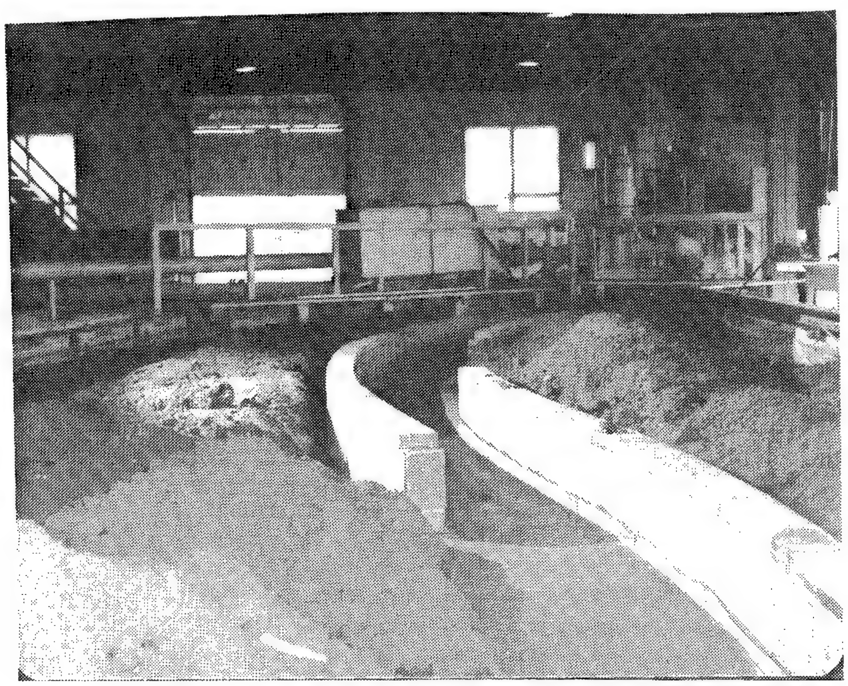
a. Bank material moving into or out of the bed zone as the dike structures were modified.

b. Degradation resulting from sediment "starvation" tests.

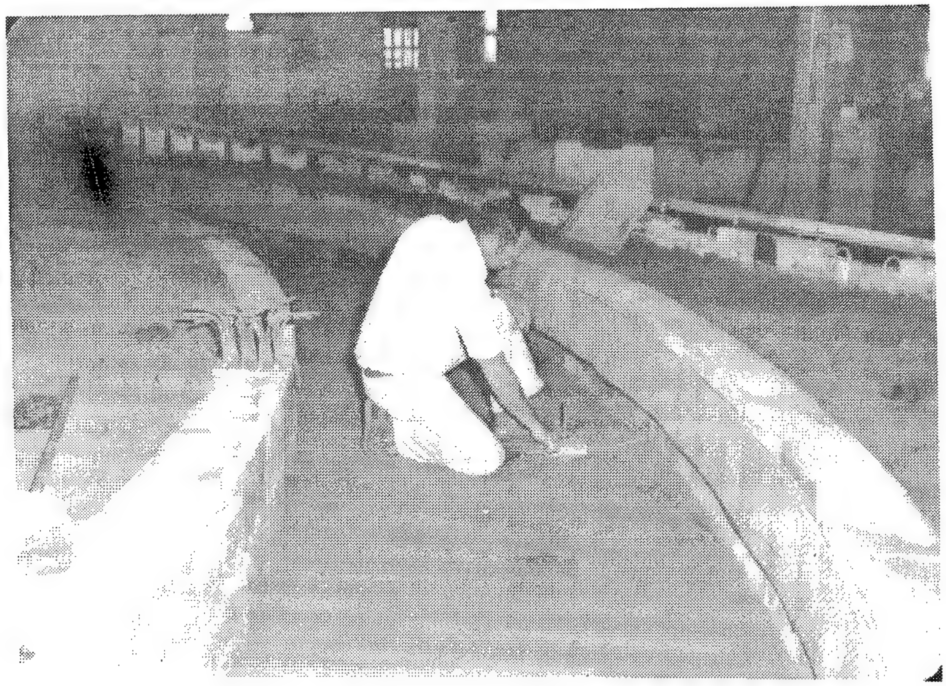
*The reader should consult Reference 2 for a more detailed explanation of the Mead Facility.



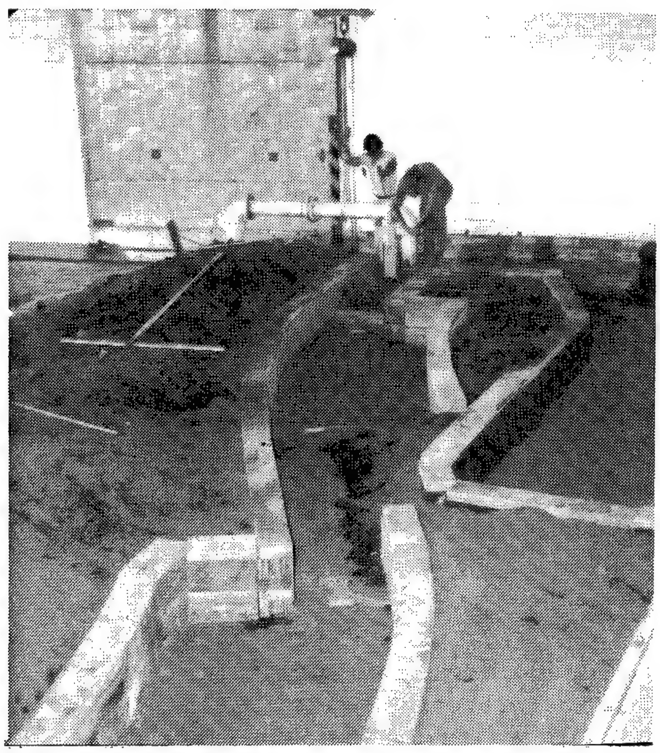
1. Measuring coordinates of river training structures on model facility overlay of hydrographic survey maps. Coordinates were used to determine location of structures in model of Browers and Snyders Bends.



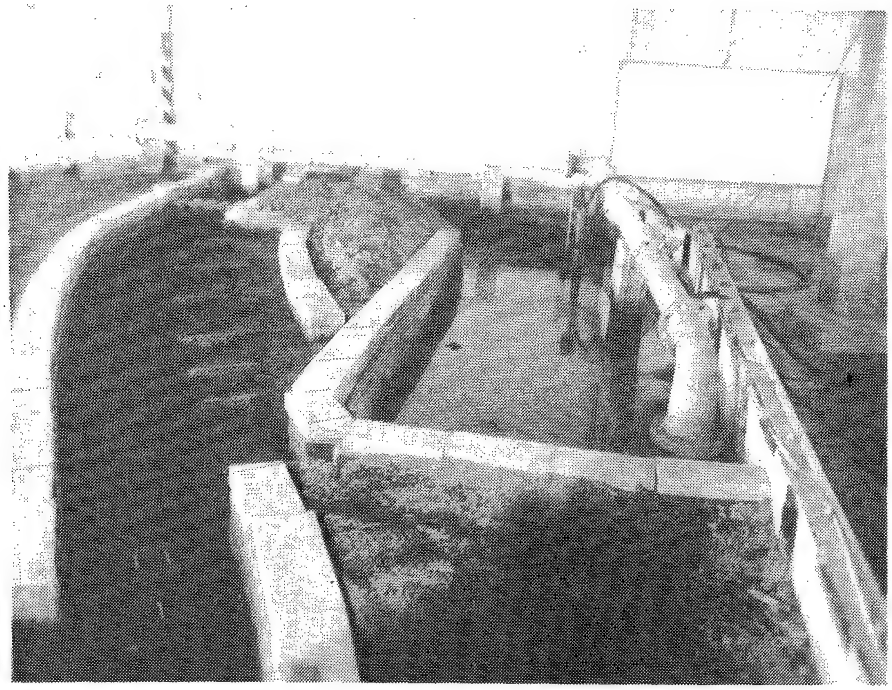
2. Concrete blocks were used to outline channel in model. View is in downstream direction at lower portion of Snyders Bend with Glovers Point Bend in background.



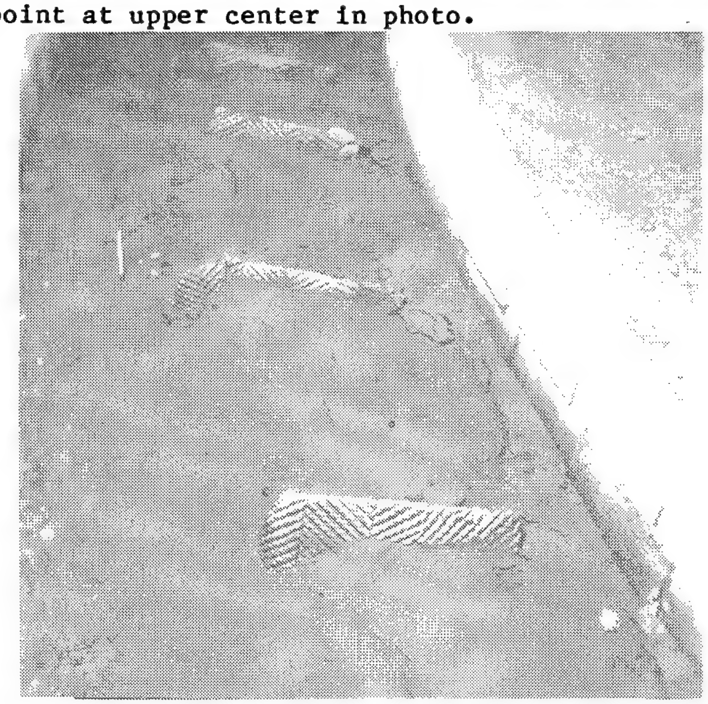
3. Placing water surface monitoring probes in model. Rack at left center of photo contains probes for remainder of model. View looking upstream at Browers Bend.



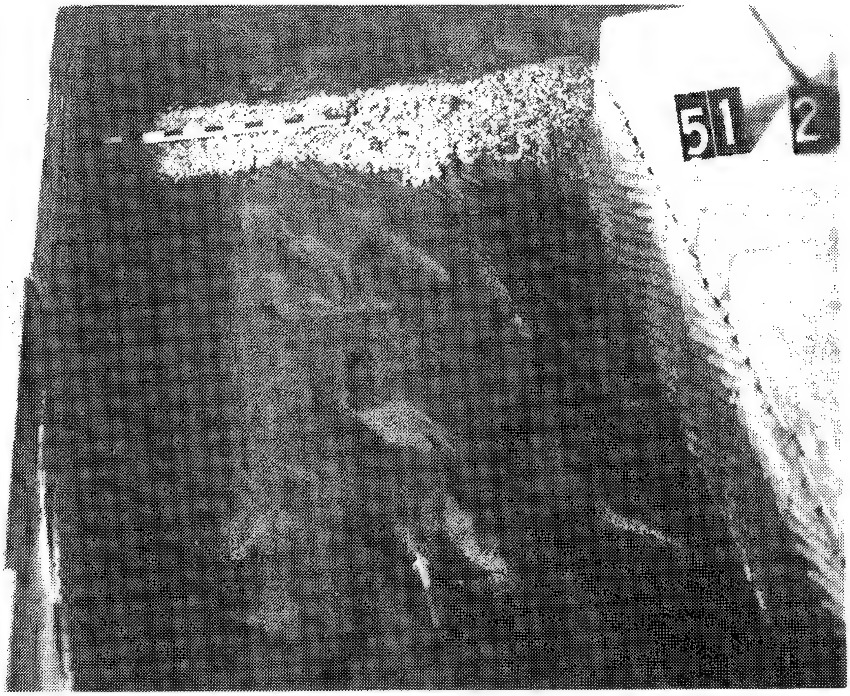
4. View in upstream direction from Browers Bend toward Omadi Bend with model entrance in background. Note tile pipe at entrance to control flow distribution. Pipe being assembled is return flow line. Settling basin for "starvation" tests is to right of entrance in photo.



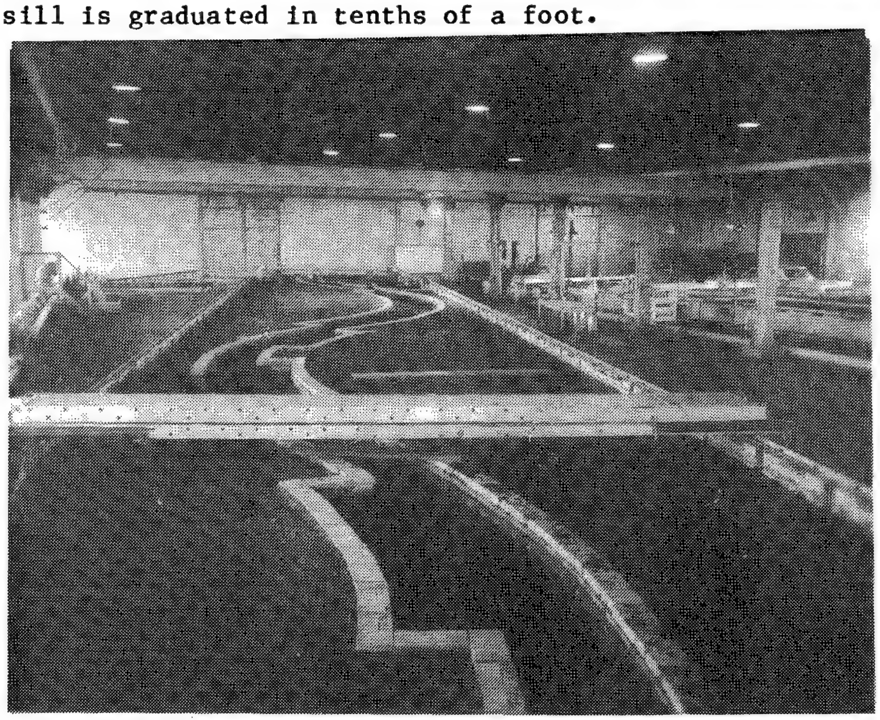
5. View of return flow line shunted into settling basin. During "starvation" tests return flow was shunted past normal reentry point into settling basin where sediment transported from model would settle. The return flow, consisting of sediment-free water, then reentered the model entrance at the normal reentry point at upper center in photo.



6. View of model dike structures in Browers Bend. Textured materials covering dikes simulated stone roughness of prototype. Second and fourth dikes in photo had sloping end sills. Dike structures could easily be removed or shifted landward to increase channel width.



7. View in upstream direction toward model grade control sill number 6 at end of run 51. Measuring device on sill is graduated in tenths of a foot.



8. View in upstream direction of model from Glovers Point Bend. Snyders Bend in middle of photo with Browers and Omadi Bends in background.

Therefore, these tests were performed while maintaining the water surface slope at a constant value. The device used to control the water surface slope, designed by Mead Hydraulic Laboratory personnel, is illustrated on Plate 4. This device allows the average bed elevation in the model to change without affecting the depth, velocity, or sediment transport rate.

11. **Slope Control Device.** The slope control device functions as follows. The water surface elevation is monitored in two stilling wells (see Plate 4) from different locations in the model. A set of electrodes in each well is used to sense the elevation of the water in that well, the normal position of each set being one electrode below the water surface and one electrode above the water surface. Both sets of electrodes are mounted to an assembly which may be either raised or lowered. One set of electrodes is fixed to the assembly, while the other set is adjustable and may be raised or lowered. The adjustable electrode set is then manipulated until the difference in the respective elevations of the two electrode sets is equal to the water surface differential required between the two locations in the model to produce the desired slope. The electrode set in the well monitoring the upstream water surface controls the assembly and will cause the assembly to raise or lower until it finds its normal position. The electrode set in the well monitoring the downstream water surface will then be in one of three positions: normal, submerged, or dry. The submerged condition would indicate that the actual water surface differential was not great enough, while the dry condition would indicate too great a differential. If the submerged condition was sensed, controls would be activated and water drained from the model until the desired conditions were met. The desired condition would be achieved when the volume of water in the model decreased and frictional elements exerted more influence on the flow, causing the water surface slope to steepen. The opposite would be true for the dry condition.

12. **Model Calibration.** Calibration tests were performed to determine the relationship between discharge, slope, and kinematic viscosity for the average depth and the sediment transport rate. Multiple regression analyses of the data determined the following relationships for this model:

$$Q_s = 28.8\ Q^{3.01}\ S^{3.95}\ V^{-2.86} \qquad (1)$$
$$D = 6.84\ Q^{0.427}\ S^{-0.360}\ V^{0.471} \qquad (2)$$

where:

Q_s = Sediment transport rate in pounds per hour
D = Average channel depth
Q = Water discharge in cubic feet per second
S = Water surface slope
V = Kinematic viscosity in square feet per second

The calibration data for the sediment transport rate and the average depth are plotted on Plate 3 versus the estimated values based on equations 1 and 2. The test data were later compared to the calibration data to determine which degradation control methods were significant in the model.

13. **Verification Tests.** In a model such as this one with a large distortion between the horizontal and vertical scales, it is important to reproduce the velocity distribution as accurately as possible.1/ Prototype velocity measurements taken at increments of 50 feet across the channel for eight different locations within the study reach were available for flow distribution comparisons. See Plate 5 for locations. These data had been obtained on 15 and 16 August 1978 when the Missouri River flow was approximately 54,000 c.f.s. For the verification tests, flow distributions for the simulated 54,000 c.f.s. flow were obtained from point-velocity measurements taken at corresponding increments across the channel for each of the eight locations. These flow distributions were compared to the flow distributions obtained at the same locations in the prototype. The incremental segment discharges in the model were found to be less than ± 5 percent of the required values; however, the overall flow distribution at each location tended to be 10 percent to 15 percent greater in that half of the channel near the concave banklines. Possibly the model concave banklines were too smooth, but efforts to roughen the concave banklines caused considerable disagreement in the flow distributions in the lower portion of the model; therefore, it was decided to not roughen the concave banklines. The results of the study, therefore, may not reflect a true prototype response.

14. **Settling Basin.** The settling basin adjacent to the entrance to the model (See Photo 5) was used for the "starvation" tests. During these tests, the return flow containing the sediment transported out of the model was shunted into the settling basin. Velocities in the basin were such that very little of the sediment was returned to the model. In this way the model was "starved" of sediment and the bed was subsequently degraded.

15. **Data Acquisition.** The duration of most tests was approximately 20 hours; however, the "starvation" tests lasted several days. During the last 3 to 4 hours of each test, the following data were obtained:

a. Discharge measurements, 1 per 30 minutes.

b. Water temperature, 1 per 30 minutes.

c. Water surface profile, 4 sets.

d. Sediment measurements, 4 samples.

At the end of each test, 30 to 40 cross sections were sounded between RM 713 and 719. This information was used to construct contour maps of the channel bed and thalweg profiles to illustrate the results of the various tests. Because of space limitations, the end portions of the model (RM 712 to 713 and RM 719 to 720) could not be sounded. They were part of the model even though they are not shown on the contour maps. Ten of the cross sections were also designated as control sections and data from these sections were used to compute the average depth and velocity of each test. These sections are labeled C-1 through C-10 on Plate 5.

IV. DISCUSSION ON TESTS

16. **General.** A total of 18 tests were performed in which various combinations of the proposed methods to control degradation were investigated. See Table I for list. In Runs 21 through 25, all 56 dike structures were removed. In Runs 41 through 45, all dike structures were shortened to provide an effective channel width of 750 feet. The end sills were removed in Runs 21 through 25 and 41 through 45. In Runs 23 through 25 and 43 through 47 the three crossing structures were each shortened by 400 feet. See Plate 8. In Runs 44 through 47, 50, and 51, seven grade control sills were constructed at approximately 1-mile intervals. See Plates 8, 9, and 10. In Runs 54 and 55, three of the grade control sills in the lower half of the model were removed. See Plates 11 and 12. Runs 40 through 46 were tested for discharge of 60,000 c.f.s. while the remaining runs were tested for a discharge of 30,000 c.f.s. Runs 51, 52, and 55 were "starvation" tests. See Plates 7, 10, and 12. Test data were compared to the calibration data by using equations 1 and 2 to estimate values of depth and sediment discharge, given the test values of water discharge, slope, and kinematic viscosity. This information is plotted on Plate 3. Bed maps and thalweg profiles were also used to compare test results. The bed map and thalweg profile from Run 48 representing the existing prototype condition in the model were used as standards to compare test results. See Plate 6.

17. **Depth Comparisons.** Comparing the information from Table I to the data in Figure 1, Plate 3, it may be determined that the observed depths in most of the runs with grade control sills were within the ±10 percent envelope. However, Run 44 falls just inside of the +10 percent envelope while Run 45 is outside of the +10 percent envelope. Both of these runs not only had grade control sills, but also included shortening of the dikes and removal of some river training structures. By contrast in Run 47, which did not include shortening of the dikes, the observed depth is in the -10 percent envelope. This would seem to indicate that the significant factors influencing depths in these runs were the increase in the effective width and the grade control sills. It may further be deduced that an increase in width produced a decrease in depth, while the grade control sills caused a slight increase in the depth. It would also indicate that the increase in width and not the removal of the training structures in Runs 22-25 was the significant factor causing the decrease in depth in these runs. In Runs 21-25 there was some loss of channel control although not as much as was expected. See Photo 9.

18. **Sediment Discharge Comparisons.** The sediment discharge data in Figure 2 of Plate 3 is very scattered; therefore, the trends are considered to be inconclusive. In Runs 22-25 the observed values of sediment discharge were much less than the calculated values, but whether this was caused by the increased width or the removal of the river training structures cannot be determined by elimination as was done in the depth comparisons. In general the following observations may be made. Except for Runs 40 and 44, all of the tests at the 60,000 c.f.s. discharge plot within the ±10 percent envelope. This would seem to imply that the degradation methods tested have little effect on the sediment discharge at high flows. For the low flows, the tests with grade control sills tend to show a slight decrease in sediment

TABLE I

COMBINATIONS TESTED OF METHODS TO CONTROL DEGRADATION

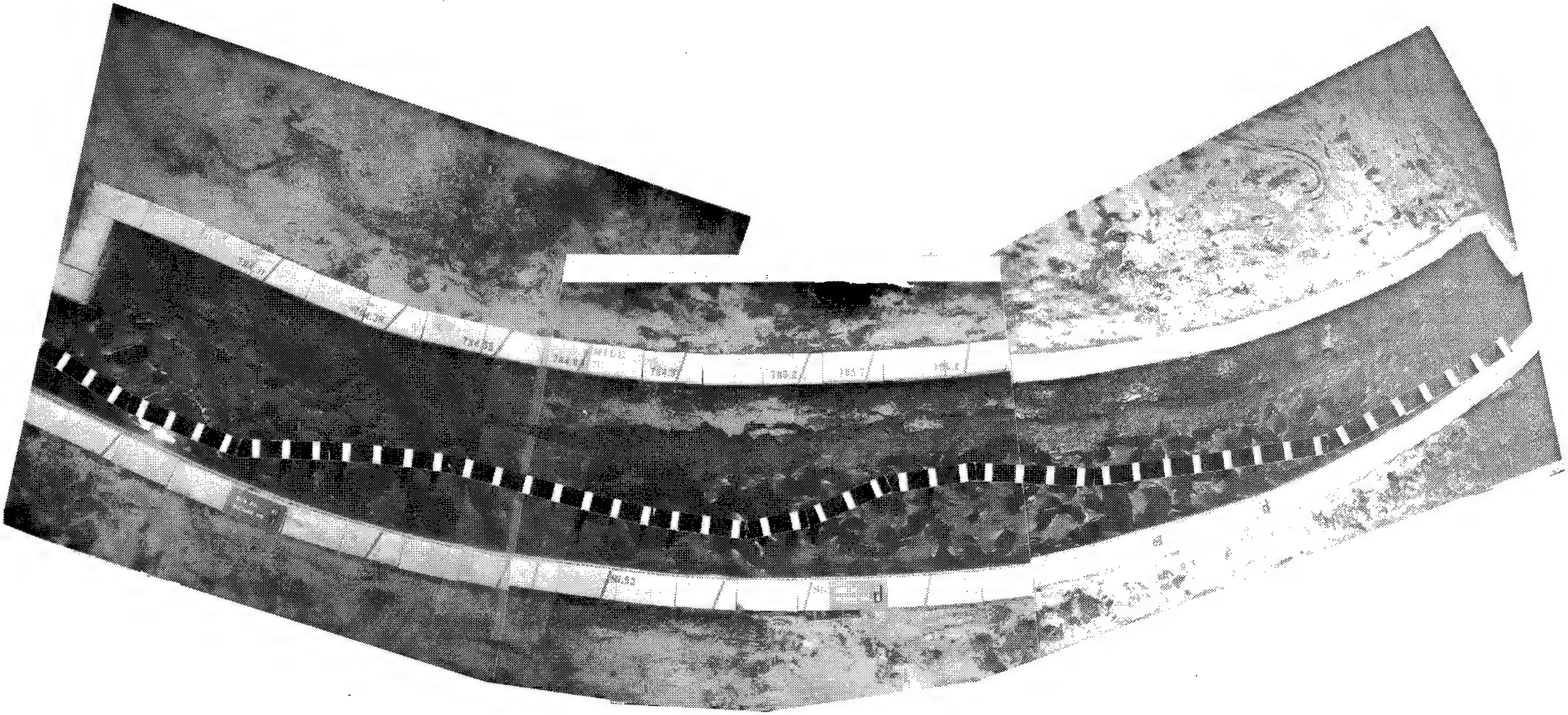
Run No.	Prototype Discharge C.F.S.	Effective Channel Width Ft.	Grade Control Structures No.	Dike Structures No.	End Sills No.	Crossing Structures	Revet. 782.3	"Starvation" Test
21	30,000	*860	0	0	0	In place	In place	No
22	30,000	*860	0	0	0	In place	In place	No
23	30,000	*860	0	0	0	Removed	In place	No
24	30,000	*870	0	0	0	Removed	In place	No
25	30,000	*900	0	0	0	Removed	Removed	No
40	60,000	600	0	56	11	In place	In place	No
41	60,000	750	0	37	0	In place	In place	No
42	60,000	750	0	37	0	In place	In place	No
43	60,000	750	0	42	0	Removed	Removed	No
44	60,000	750	7	42	0	Removed	Removed	No
45	60,000	750	7	42	0	Removed	Removed	No
46	60,000	600	7	56	11	Removed	Removed	No
47	30,000	600	7	56	11	Removed	Removed	No
50	30,000	600	7	56	14	In place	In place	No
51	30,000	600	7	56	14	In place	In place	Yes
52	30,000	600	0	56	14	In place	In place	Yes
54	30,000	600	4	56	14	In place	In place	No
55	30,000	600	4	56	14	In place	In place	Yes
48**	30,000	600	0	56	14	In place	In place	No

*Average top width of control sections
**Existing Conditions

discharge over the calculated values. It should be noted that these runs also show a slight increase in depth over the calculated values. See Figure 1, Plate 3.

19. **Bed Map and Thalweg Profile Comparisons for Grade Control Sills.** Considering that the grade control sills at the 30,000 c.f.s. flow condition tended to increase the flow depth and decrease the sediment discharge, it would appear that this method may have merit as a way to reduce channel degradation. Comparing Run 50 from Plate 9, which contained 7 grade control sills, to Run 48 from Plate 6, which represents the existing prototype condition, no significant differences except at the sill locations are discernible. In fact, it would appear that the grade control sills have no effect whatsoever. In Run 51, the return flow was shunted through the settling basin, causing very little sediment to reenter the model. This test continued for 123 model hours, almost 6 times as long as Run 51. During this period the water surface dropped about 1.5 feet, while the thalweg degraded about 4 feet. See Plate 10. It would also appear that more degradation occurred in the upper end of the model than occurred in the lower end. The sediment discharge during this time decreased from 8 lb/hr to 3 lb/hr. This would indicate that the grade control sills did in fact fix the water surface elevations and thereby slowed the degradation process. Since the clear water entering the upper portion of the model had a greater potential for erosion than did the water in the lower portion, which was carrying sediment, the upper portion eroded more than the lower portion. Runs 54 and 55 were similar to Runs 50 and 51 except that only the four upstream grade control sills were placed in the model. The slope control device was also changed so that it only controlled the slope downstream of the grade control sills. This essentially allowed the reach with the grade control sills to function without any external controls. In Run 54 the sediment was recirculated along with the water. This test continued for 95 hours with no change in water surface elevations and no significant change to the thalweg. See Plate 11. In Run 55 the flow was again shunted through the settling basin. This test lasted 172 hours and produced various degrees of degradation. See Plate 12. Because of the high velocities over Sill 3, stones from the crest of this structure were eroded lowering the sill about 4 feet. The amount of degradation which occurred in the reaches between Sills 3 and 4 and downstream of Sill 4 was about the same as the change in water surface elevations. The degradation in the reaches between Sills 1 and 2 and Sills 2 and 3 was greater than the change in water surface elevation. Again this may be attributed to the clear water at the upper end of the model having a greater potential to erode material than the water with sediment at the lower end. During Run 55 the sediment discharge remained relatively constant at about 12 lb/hr and was probably caused by the constant rate of erosion in the lower portion of the model. The above results from the grade control sill tests seem to conflict but in actuality they conform to well known principles on sills.

20. **Sill Flow Regimes.** There are three flow regimes for sills; free flow, partially submerged, and fully submerged.[3/] The submerged condition occurs when the water elevation downstream of the sill is higher than the sill elevation.



9. Overhead view of Browers Bend at end of Run 21 in which all dike structures had been removed. Flow was from right to left in photo. Note tendency of flow to meander in downstream half of bend as a result of dikes being removed.

a. **Free Flow.** For the free flow condition the downstream water surface elevation is below the sill elevation. Critical depth occurs over the sill and consequently the downstream water elevation has no influence on the upstream elevation. The upstream headwater may be determined from the following:

$$H_1 = \left(\frac{Q_1}{CL}\right)^{0.67} \tag{3}$$

where

H_1 = Height of water above sill crest on upstream side of sill, ft.
Q_1 = Discharge over sill, c.f.s.
C = Coefficient, model value determined to be about 3.1
L = Horizontal crest length of sill, ft.

For a discharge of 30,000 c.f.s. and a crest length of 600 feet the upstream headwater should be about 6.4 feet above the sill crest. This condition was approached in Run 55, when the head upstream of Sill 4 was about 8 feet, but because of the high velocities over the sill the stone in the sill crest was eroded preventing free flow from occurring. See Plate 12.

b. **Partially Submerged Flow.** In the partially submerged condition, water surface elevations upstream of the sill are influenced by the sill and the downstream water elevation. The following formula may be used to determine the upstream water elevation.

$$\frac{Q}{Q_1} = \left(1 - \left(\frac{H_2}{H_1}\right)^{1.5}\right)^{0.385} \tag{4}$$

where

Q = Discharge over sill, c.f.s. (submerged)

H_2 = Height of water above sill crest on downstream side of sill, ft.

Q_1 = Discharge resulting from H_1 if sill not submerged

$= CLH_1^{\ 1.5}$

The other quantities are as defined previously. The sills in Runs 51 and 55 were partially submerged. In Run 55, the calculated values of H_1, using equation 4 and H_2 values obtained from the water surface profile, agree very favorably with the H_1 values from the water surface profile. See Table II and Plate 12.

TABLE II
Calculated and Observed
Heads on Sills for Run 55

Sill No.	H_1 (ft.)	H_1^* (ft.)	H_2 (ft.)
4	8.6	8.2	6.0
3	9.0	8.7	6.9
2	8.8	9.3	7.8

*Calculated

For a series of closely spaced sills such as those used in Run 51, if the assumption is made that the backwater effects from each sill do not diminish significantly in the distance between sills, then the headwater height (H_1) on a downstream sill will be approximately equal to the tailwater height (H_2) on the next sill upstream. In Run 51 there were no abrupt changes in the water elevations over the sills to indicate that the sills were influencing the water elevations. However, by using the water surface profile from Plate 10, the height of water over the sills, H, can be shown to conform reasonably with calculated values from equation 4 assuming the downstream H_1 equal to the upstream H_2. See Plate 10 and Table III.

TABLE III
Calculated Heads on Sills for Run 51 vs
Height of Water Over Sills

Sill No.	H_1 (ft.)	H_2 (ft.)	H^* (ft.)
6	0.170	0.142	0.175
5	0.190	0.170	0.190
4	0.206	0.190	0.195
3	0.218	0.206	0.195
2	0.228	0.218	0.225

*Measured from Plate 10

The data in Table III is presented in model rather than prototype dimensions because the relationship in equation 4 cannot be expressed as a ratio. Therefore, the vertical scale ratio of 1:52 is not applicable. The slope control device limited the total head loss in the model to about 0.07 feet. The average head loss at each sill then was about 0.01 feet, not too obvious. This flow condition then forced the flow regime to be very nearly fully submerged. If the slope control had been set for a steeper slope, the degree of submergence at each sill would have been less.

c. **Fully Submerged Flow** When the ratio of H_2/H_1 exceeds about 0.95 a sill may be considered fully submerged. The sill then will have no influence on the water elevations. This was true for Runs 50 and 54 and for the first few hours of operation in Runs 51 and 55 before degradation dropped the water elevation into the partially submerged regime. If the sills in the fully submerged condition have no influence on the water elevations, it would be expected that they would not influence the sediment discharge or the bed elevations. This was confirmed in Runs 50 and 54 in which the bed maps and thalweg profiles differed little from the existing condition, Run 48, with no grade control sills. Compare Plates 9 and 11 to Plate 6.

V. CONCLUSIONS

21. Test results were evaluated by comparing the average depth and sediment discharge from each test to calculated values from empirical relationships derived from calibration tests. Also bed contour maps and thalweg profiles were used to visually compare test results to the existing condition bed contour map and thalweg profile duplicated in the model. It should be noted that this model study did not duplicate degradation which had occurred in the Browers Snyders Bends but only provided means of evaluating the effects of certain structural alterations on the average depth and sediment discharge in this model. Also, not taken into consideration in the model study was the effects of channel bed armoring which is known to affect degradation in this part of the Missouri River. Because of the large distortion between the horizontal and vertical model scales, the results of this study may not directly apply to Browers Snyders Bends.

22. Comparisons of the test data to the empirical data indicated that the removal of all dike structures would increase the channel width about 45 percent, decrease the average depth about 20 percent, and decrease the sediment discharge about 50 percent. See Plate 3 and Table I. There was some loss of channel control as a result of removing all the dike structures. See Photo 9. Shortening the dikes by 150 feet caused about a 10 percent decrease in depth. It could not be determined if shortening of the dikes had a significant effect on the sediment discharge. See Plate 3 and Table I. The tests on the grade control sills in general showed that they caused less than a 10 percent increase in depth but could possibly decrease the sediment discharge by as much as 40 percent. A series of closely spaced grade control sills would seem to offer the best solution to reducing channel degradation. However, it must be realized that the sills will not influence the upstream water or bed elevations unless there is positive control of the water elevation at the most downstream sill. Positive control may be provided by such methods as a dam or critical depth. As such, this would preclude the use of sills in the navigation portion of the Missouri River. However, they may be used successfully in non-navigation streams.

23. **Additional Comments on Grade Control Sills.** With a series of grade control sills, there are multiple design features possible at each sill with multiple results at each discharge for the sill system. Therefore, the system must be thoroughly analyzed for the entire range of expected flows. It is suggested that the sills be closely spaced so that the backwater and

submergence effects work together. It must be realized that there has to be positive control of the water elevations at the most downstream structure or else degradation will continue within the system of sills until critical depth occurs to produce a positive control. If the sills are not designed for the high velocities at critical depth, they will fail. Even when the system is properly designed, there will initially be a certain amount of degradation depending upon the sediment loads and the range of discharges controlled by the sills. Degradation within the system will progress until depth and velocities within the various segments are attained such that the amount of sediment entering the system is equal to the amount leaving the system. If the sill system is designed to be fully submerged over a large range of the expected flows, the sills will be ineffective and degradation will not be stopped.

APPENDIX A

References

REFERENCES

1. American Society of Civil Engineers, "Hydraulic Models," ASCE Manuals of Engineering Practice No. 25.

2. Missouri River Division, Corps of Engineers, "Operation and Function of the Mead Hydraulic Laboratory," MRD Hydraulic Laboratory Series Report No. 1, March 1969.

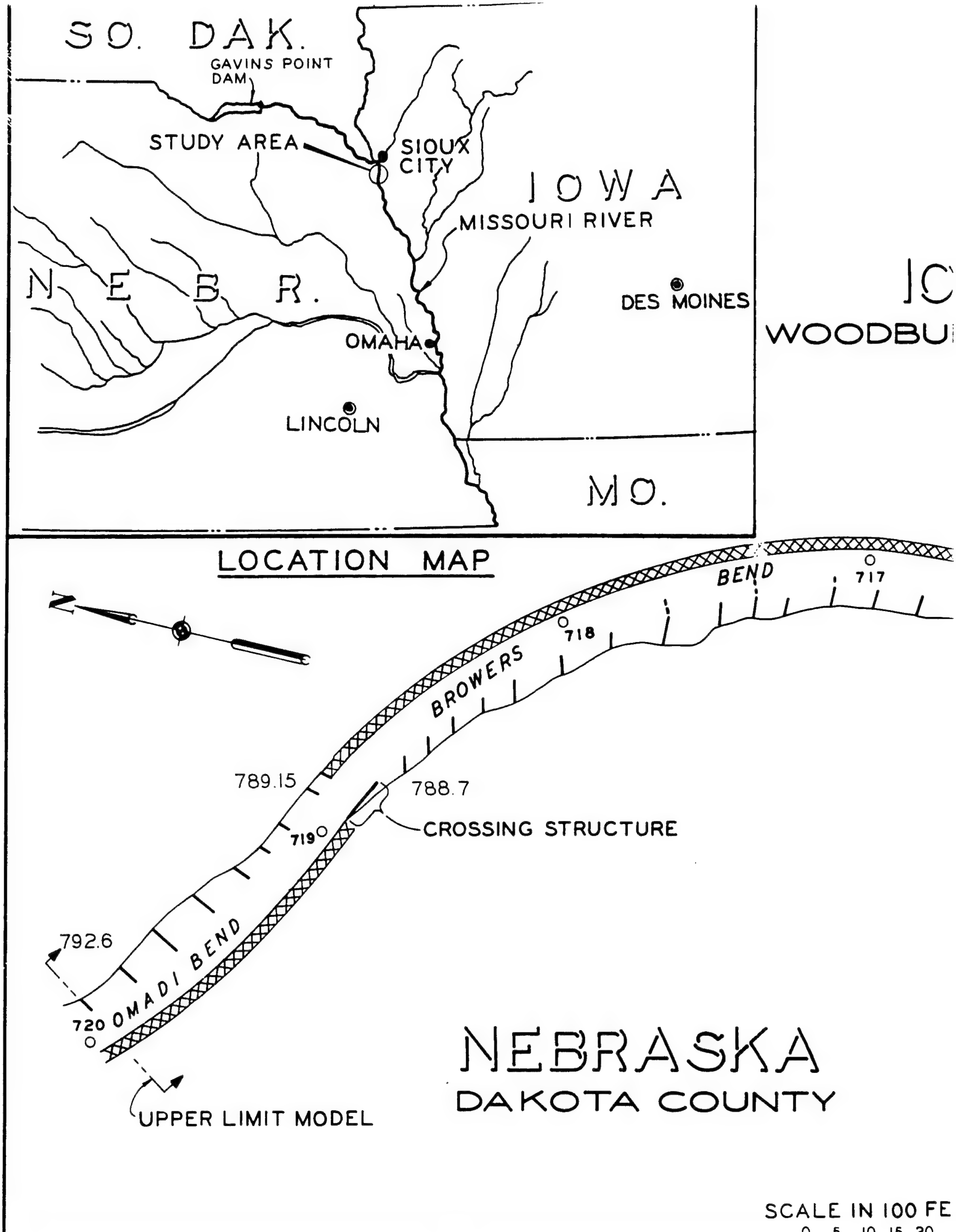
3. King, Horace Williams and Ernest F. Brater, "Handbook of Hydraulics," McGraw-Hill Book Company, Fifth Edition.

4. U.S. Army Engineer District, Omaha, Corps of Engineers, "Missouri River Hydrographic Survey," November 1976.

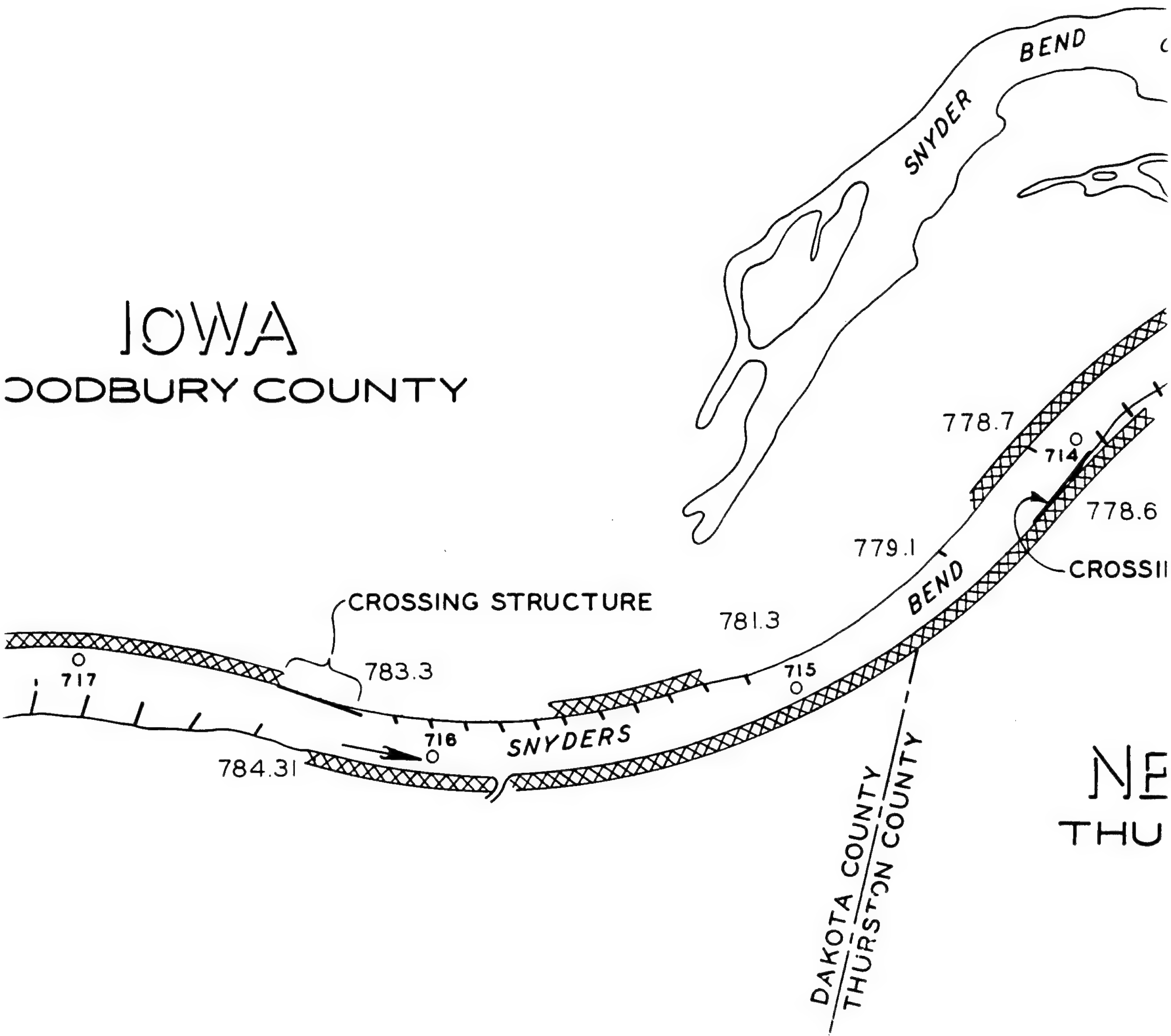
5. U.S. Army Engineer District, Omaha, Corps of Engineers, "Construction Completion Reports R. M. 712 to R. M. 720," not published.

6. U.S. Army Engineer District, Omaha, Corps of Engineers, "Review Report for Water and Related Land Resources Management Study," Volume IV, Supporting Technical Report - Missouri River Degradation, August 1981.

APPENDIX B
Plates



SO. DAK.
GAVINS POINT DAM
STUDY AREA
SIOUX CITY
IOWA
MISSOURI RIVER
NEBR.
DES MOINES
OMAHA
LINCOLN
MO.
LOCATION MAP
IO
WOODBU
BEND
717
718
BROWERS
789.15
788.7
719
CROSSING STRUCTURE
792.6
OMADI BEND
720
UPPER LIMIT MODEL
NEBRASKA
DAKOTA COUNTY
SCALE IN 100 FE
0 5 10 15 20

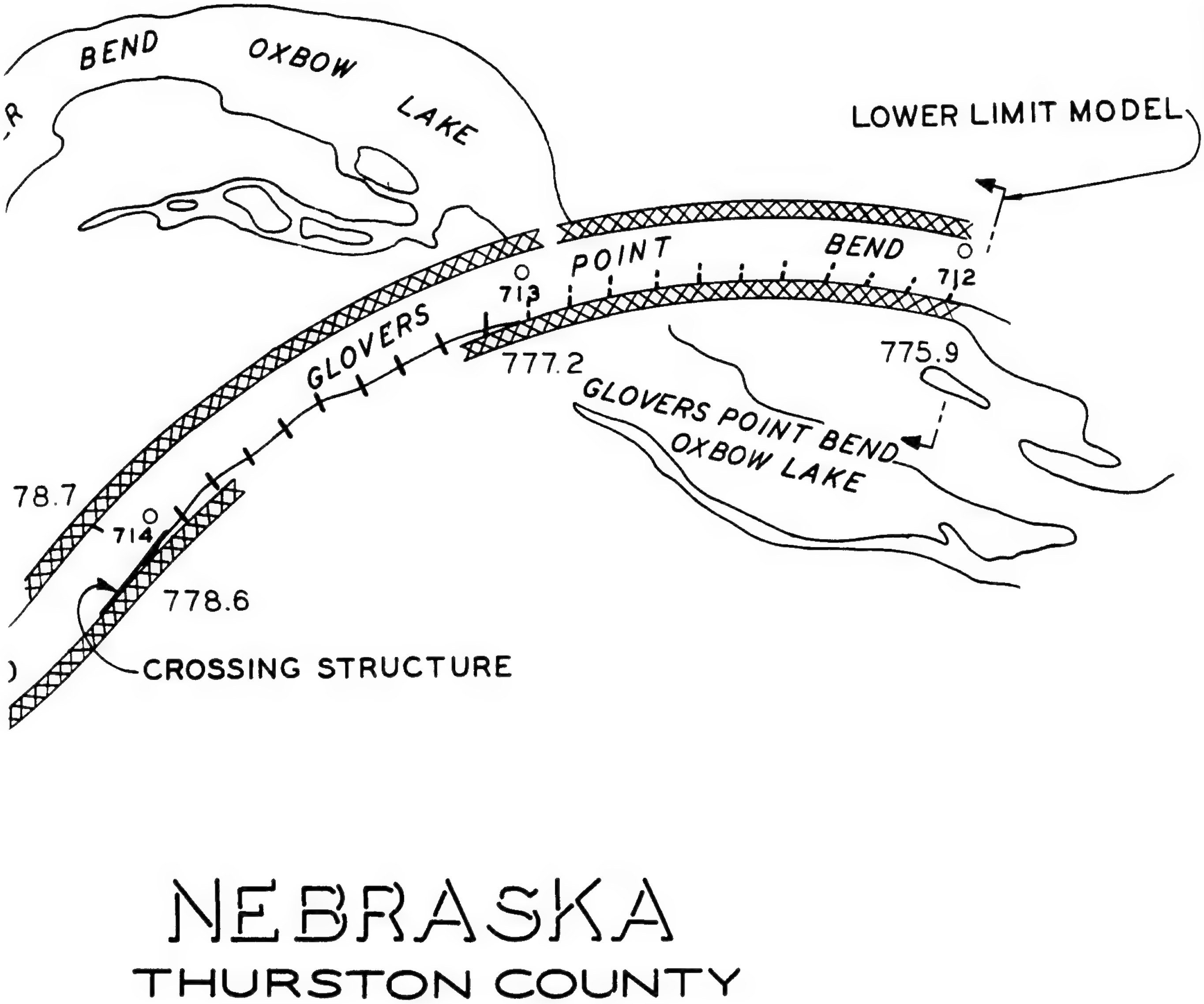


LEGEND:

717	RIVER MILE (1960)
XXX	STONE FILL REVETMENT
-- —777.2	STONE FILL DIKE AND NUMBER SILL INDICATED BY DASHED LINE

LE IN 100 FEET

5 10 15 20



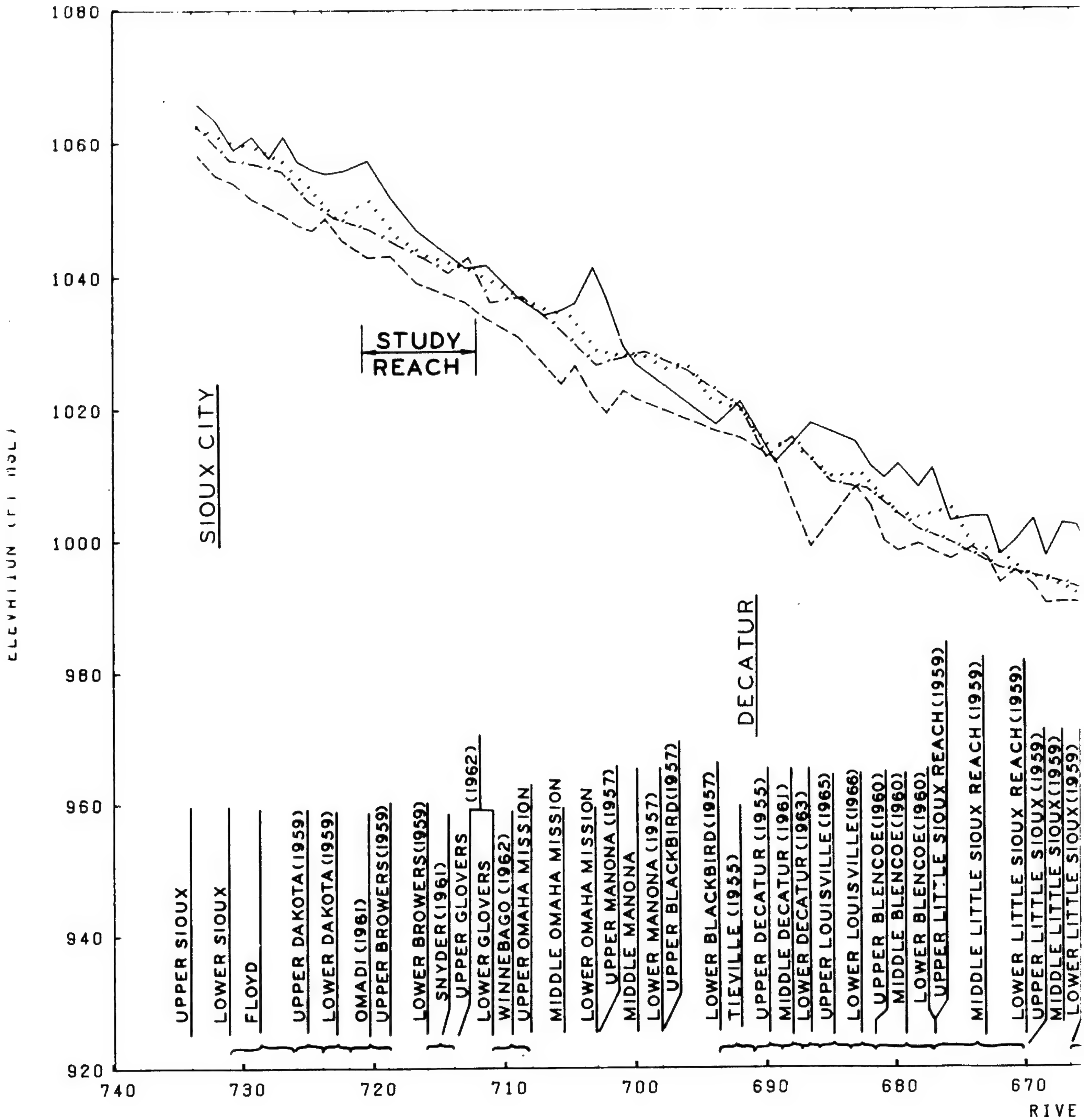
MEAD HYDRAULIC LABORATORY

DEGRADATION STUDY

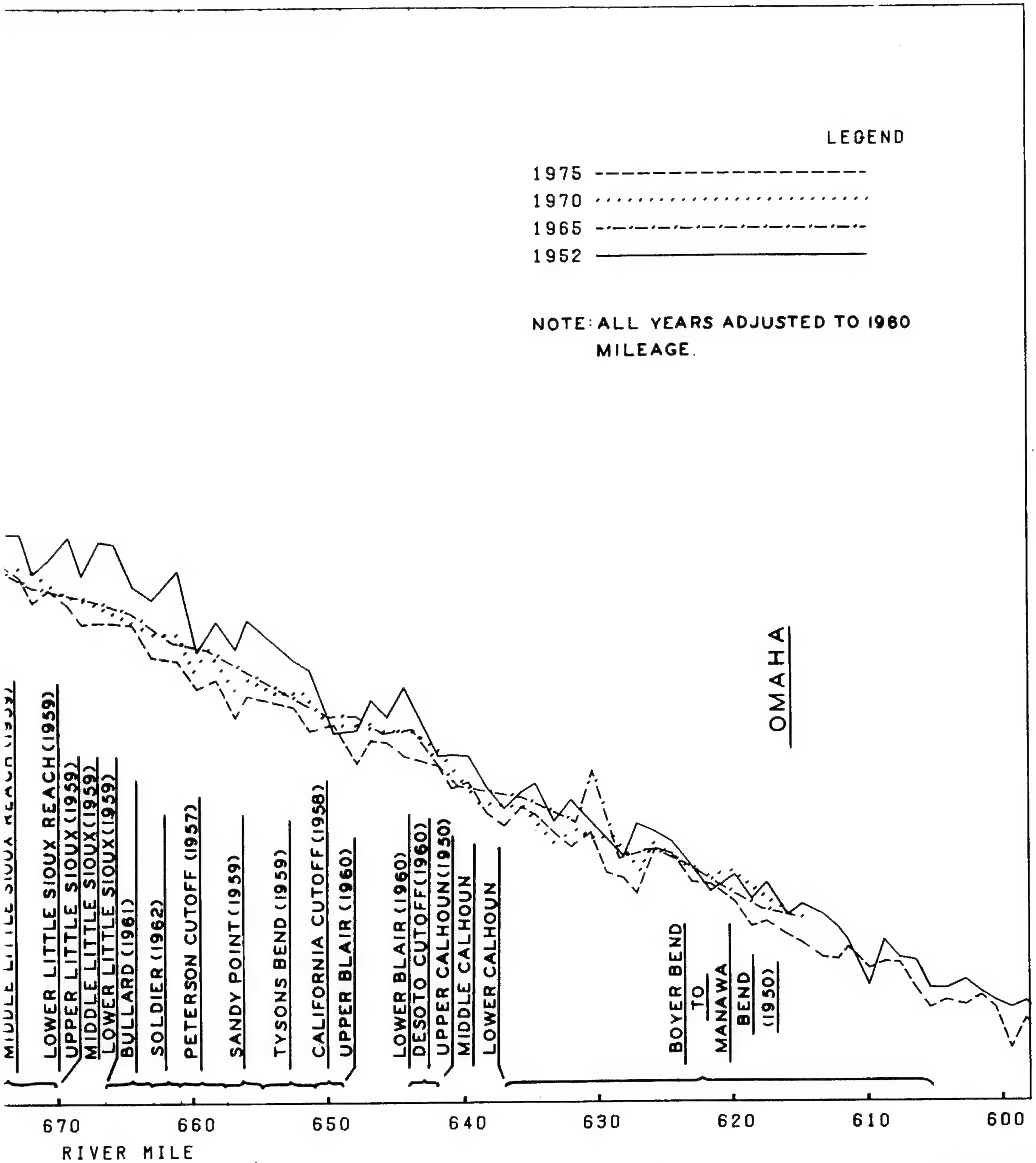
LOCATION MAP AND STUDY AREA

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

PLATE I



HISTORIC MISSOU



IC MISSOURI RIVER THALWEG

MEAD HYDRAULIC LABORATORY
DEGRADATION STUDY
HISTORIC MISSOURI RIVER THALWEG
U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

2

PLATE 2

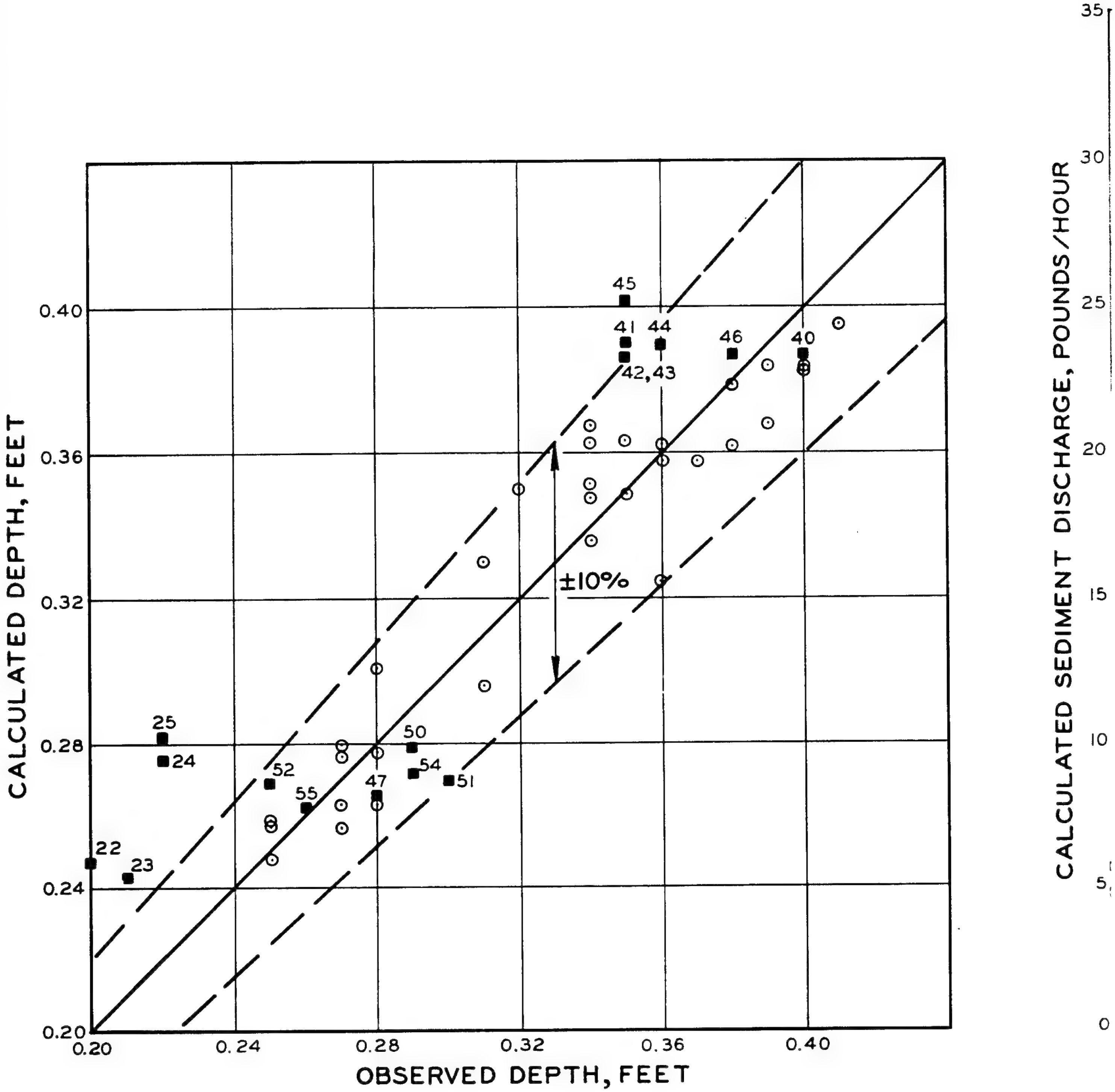


FIGURE 1

NOTE: Number by symbols are
See Table 1 for test

LEGEND:
⊙ Calibration Data
■ Test Data

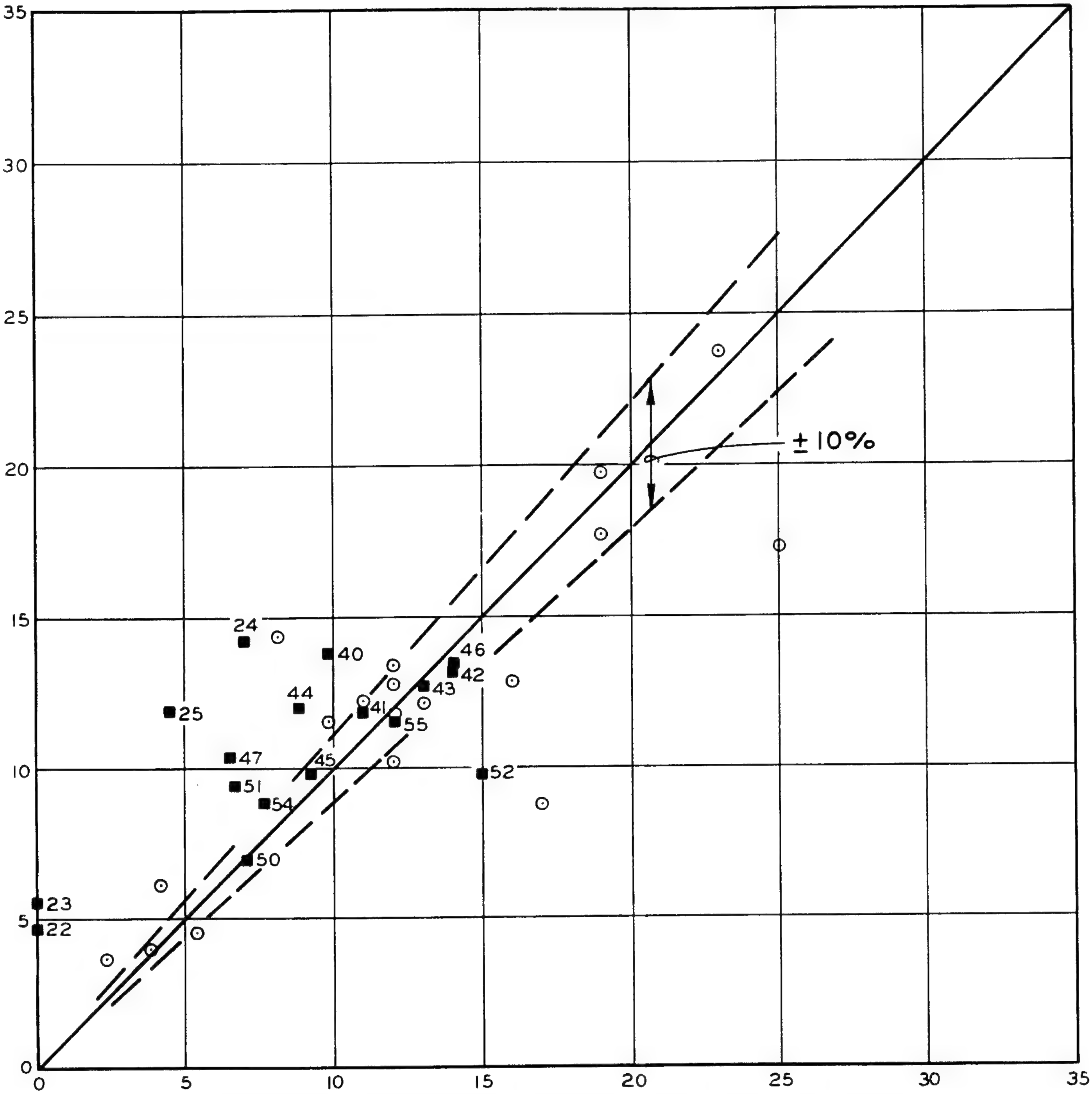


FIGURE 2

are test numbers.
st parameters.

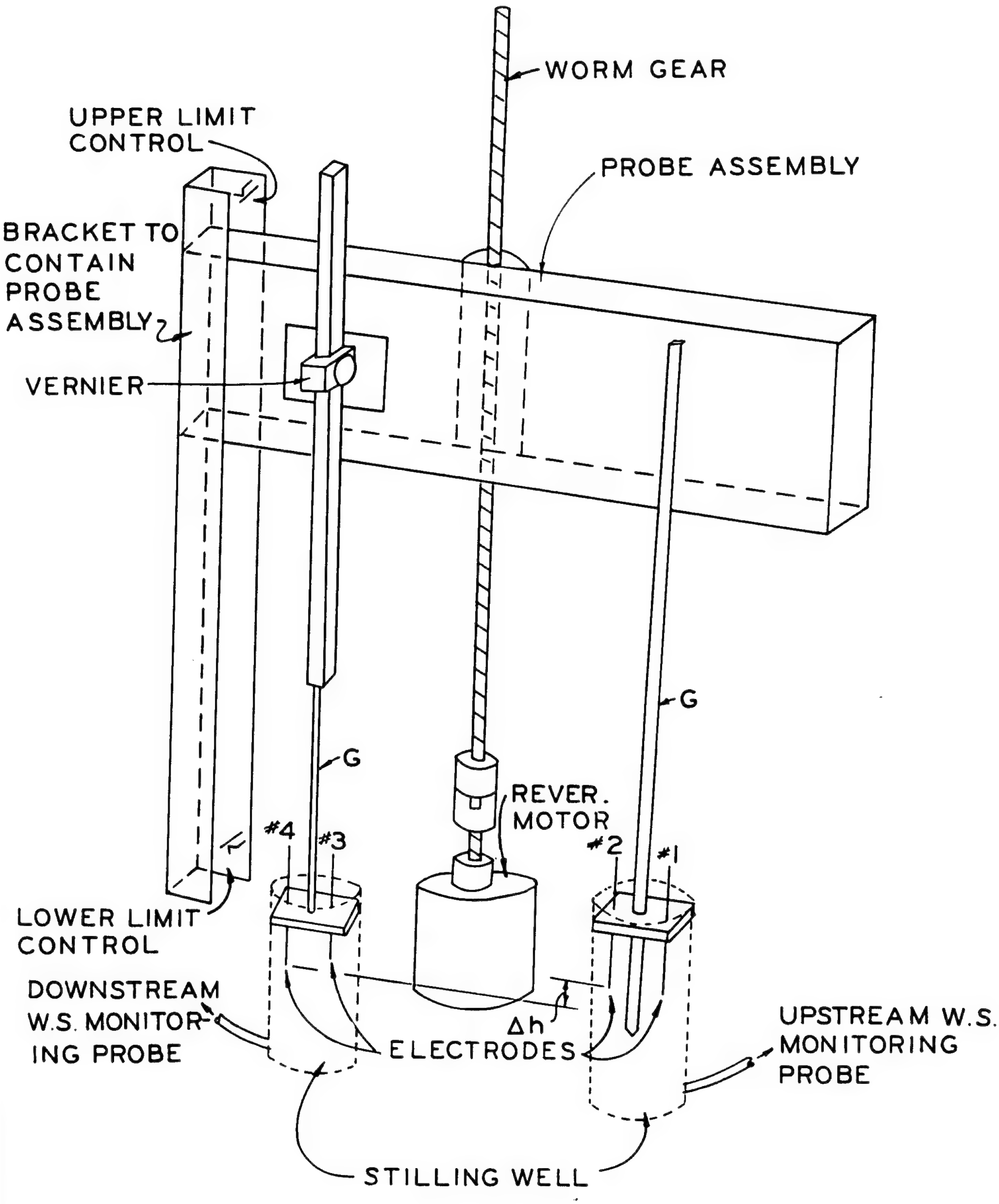
MEAD HYDRAULIC LABORATORY

DEGRADATION STUDY

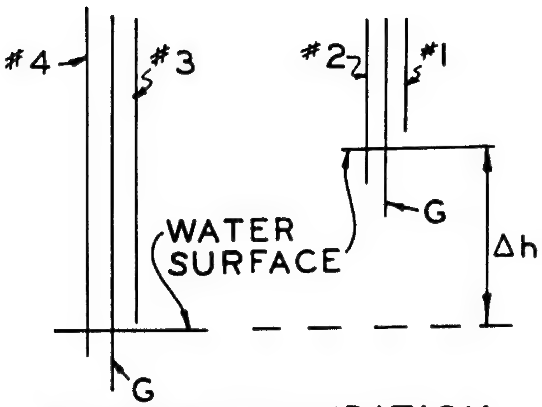
OBSERVED VS. CALCULATED VALUES
OF DEPTH AND SEDIMENT DISCHARGE

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

(2)



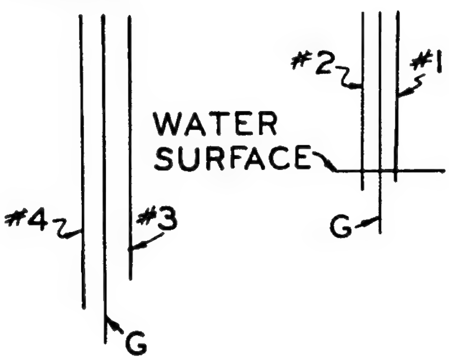
SLOPE CONTROL DEVICE
(PARTIAL VIEW)



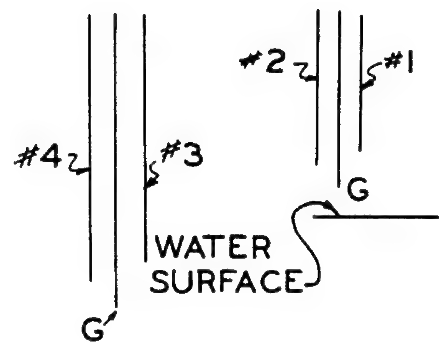
DESIRED CONDITION

SLOPE = Δh / DIST. BETWEEN WATER SURFACE MONITORING PROBES

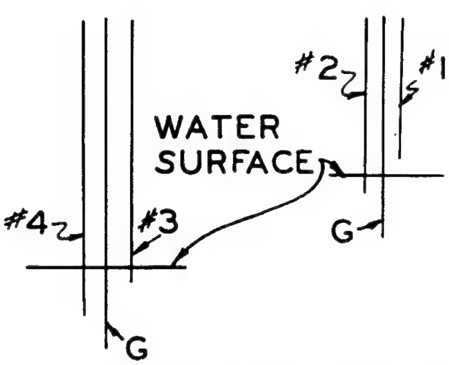
POSSIBLE CIRCUIT COMBINATIONS	
WATER CONTROL	UP/DOWN CONTROL
#4 — G O.K.	#2 — G O.K.
#4 —⁄— G ADD WATER	#2 —⁄— G LOWER PROBES
#3 — G TAKE OUT WATER	#1 — G RAISE PROBES



RAISE PROBES

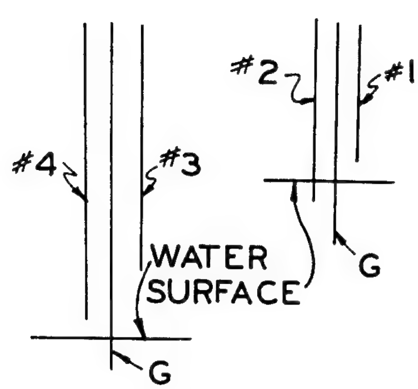


LOWER PROBES



TAKE OUT WATER

SLOPE TOO FLAT



ADD WATER

SLOPE TOO STEEP

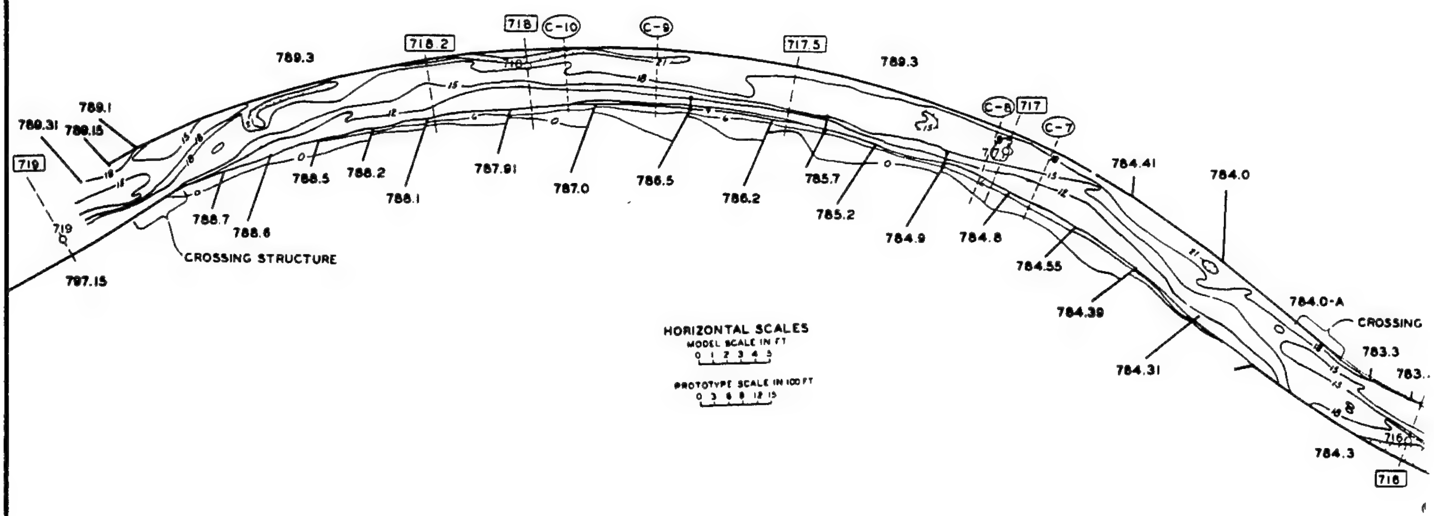
MEAD HYDRAULIC LABORATORY

DEGRADATION STUDY

SLOPE CONTROL DEVICE

2

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA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784.9
784.8
C-8
717
C-7
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784.0-A
CROSSING
783.3
784.3
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CROSSING STRUCTURE
HORIZONTAL SCALES
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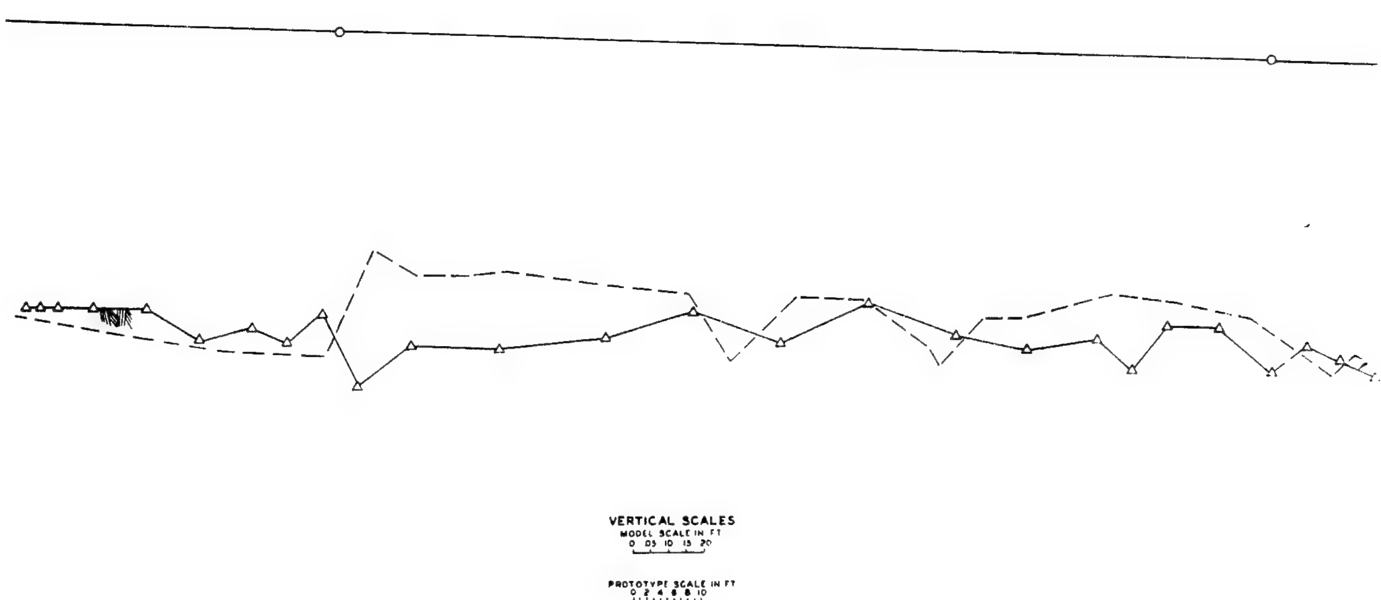
PROTOTYPE SCALE IN 100 FT
0 3 6 9 12 15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MODEL SCALE IN FT
PROTOTYPE SCALE IN FT
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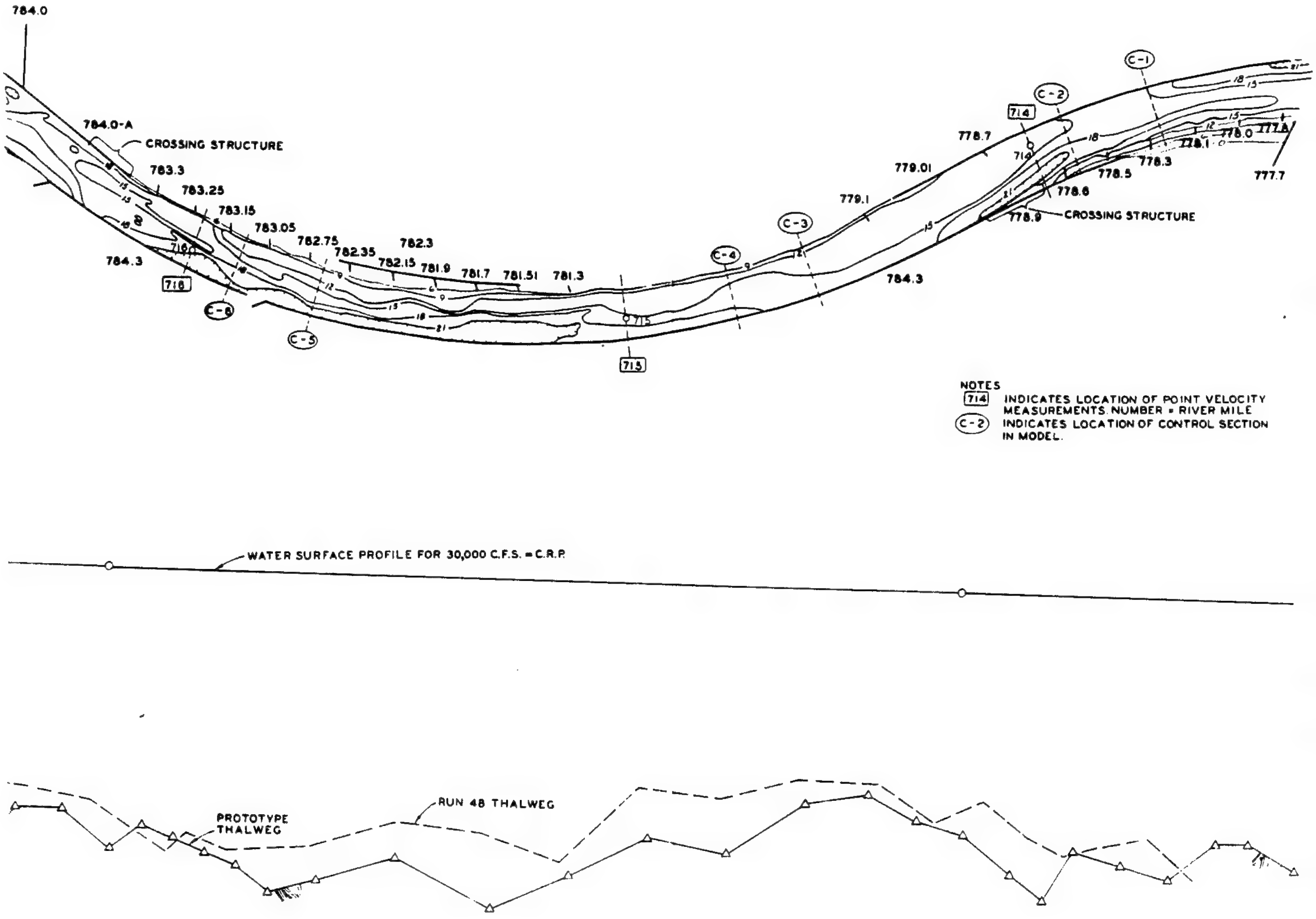


MEAD HYDRAULIC LABORATORY

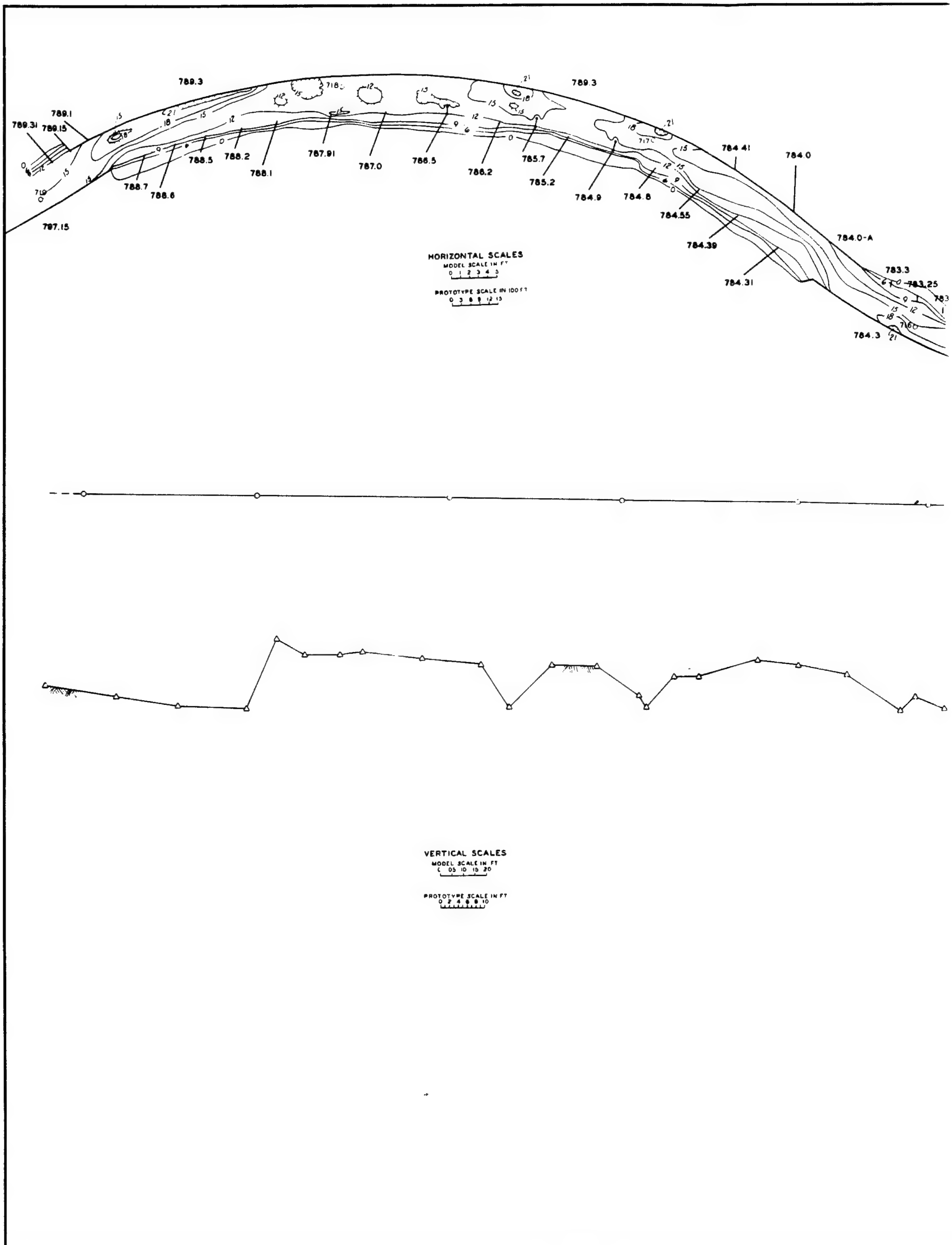
DEGRADATION STUDY

PROTOTYPE BED CONTOURS AND THALWEG

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

(2)

PLATE 5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HORIZONTAL SCALES
MODEL SCALE IN FT
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PROTOTYPE SCALE IN 100 FT
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MODEL SCALE IN FT
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PROTOTYPE SCALE IN FT
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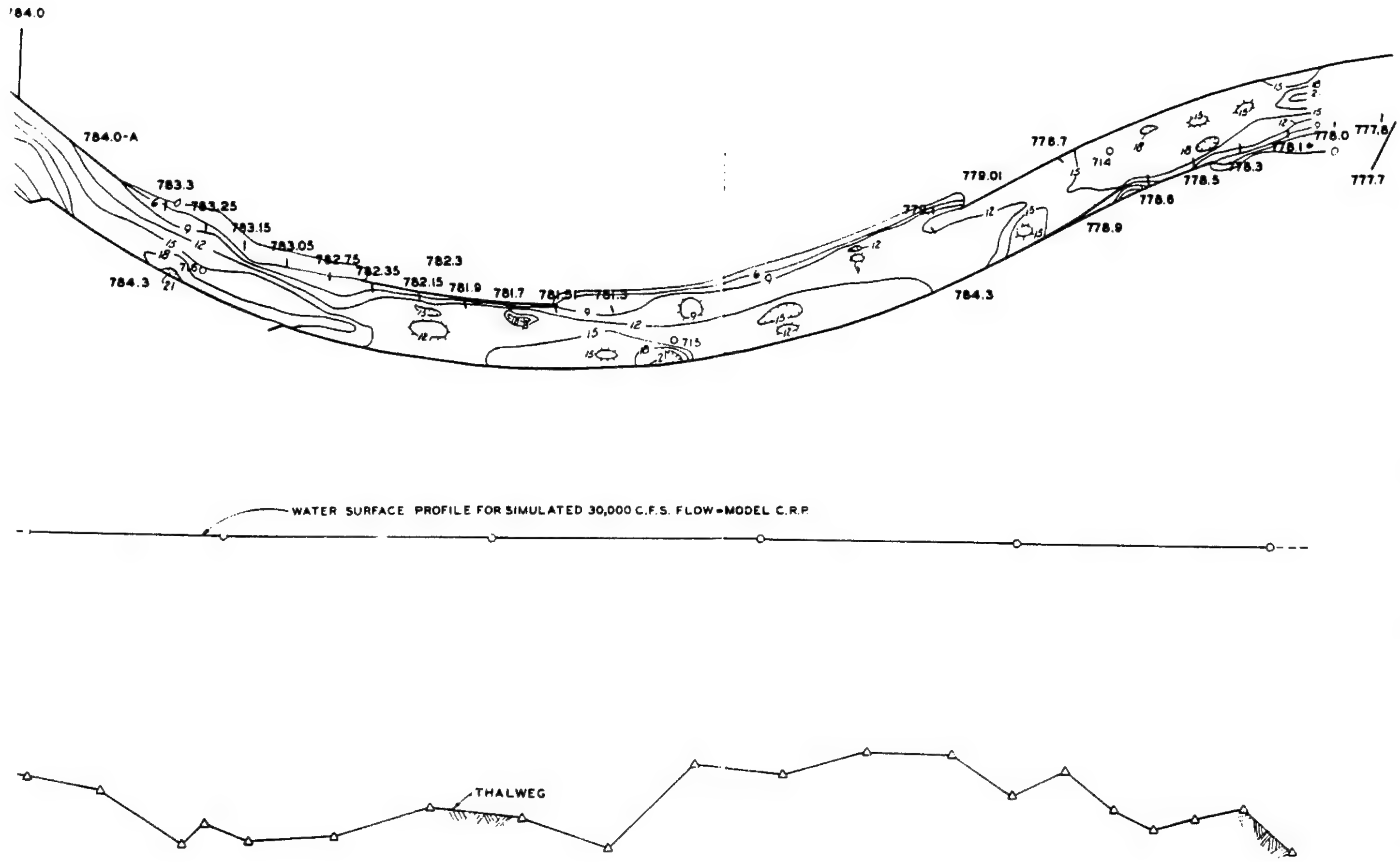
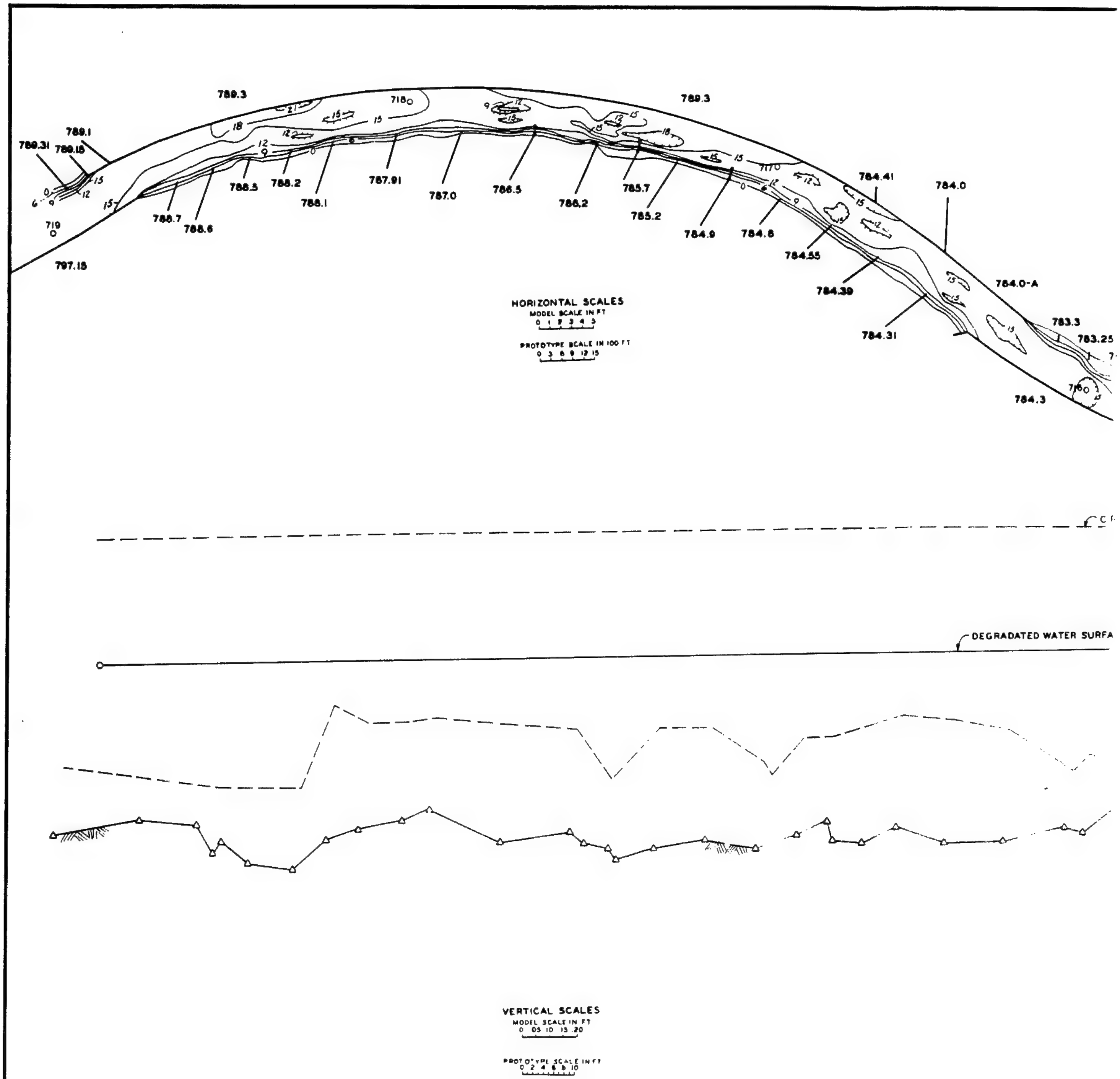


NOTES:

1. Prototype conditions
2. Discharge = 30,000 cfs with sediment recirculation.

THIS DRAWING HAS BEEN REDUCED TO THREE-EIGHTHS THE ORIGINAL SCALE.

MEAD HYDRAULIC LABORATORY
DEGRADATION STUDY
RUN 48
U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA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HORIZONTAL SCALES
MODEL SCALE IN FT
0 1 2 3 4 5
PROTOTYPE SCALE IN 100 FT
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MODEL SCALE IN FT
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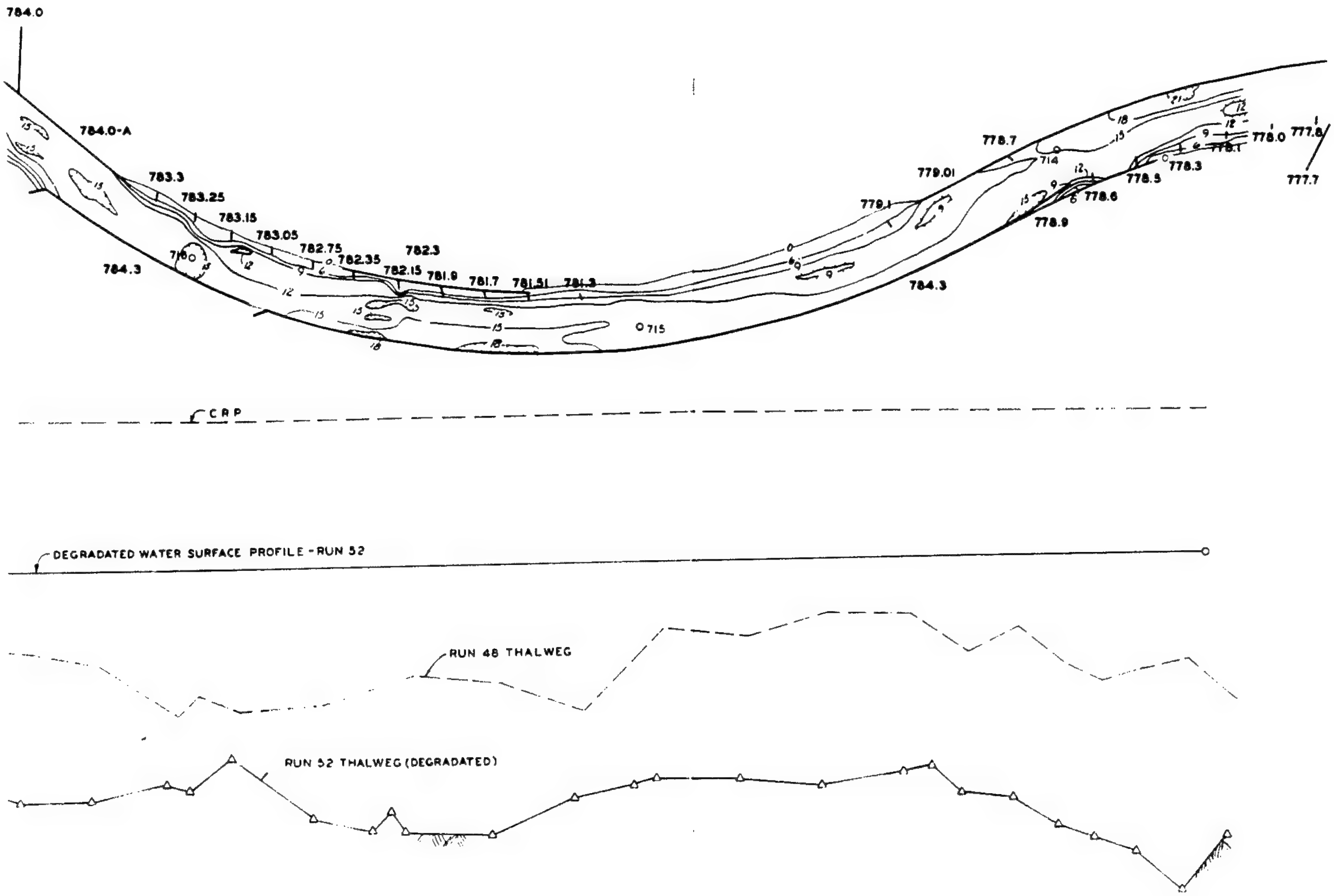
PROTOTYPE SCALE IN FT
0 2 4 6 8 10



NOTES:

1. Prototype conditions
2. Discharge = 30,000 cfs

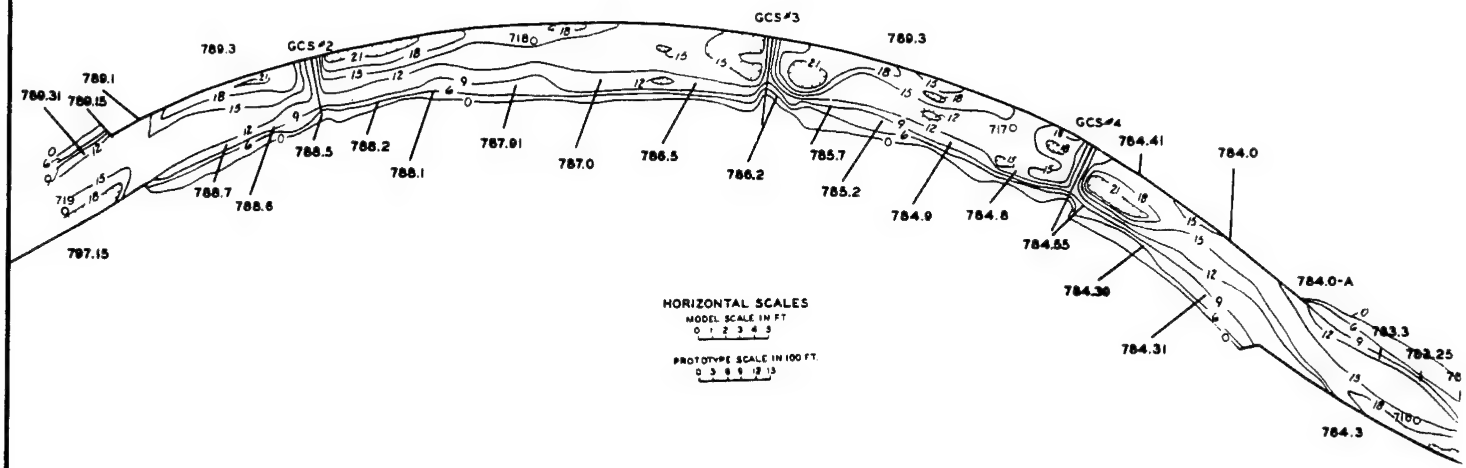
MEAD HYDRAULIC LABORATORY

DEGRADATION STUDY

RUN 52

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

2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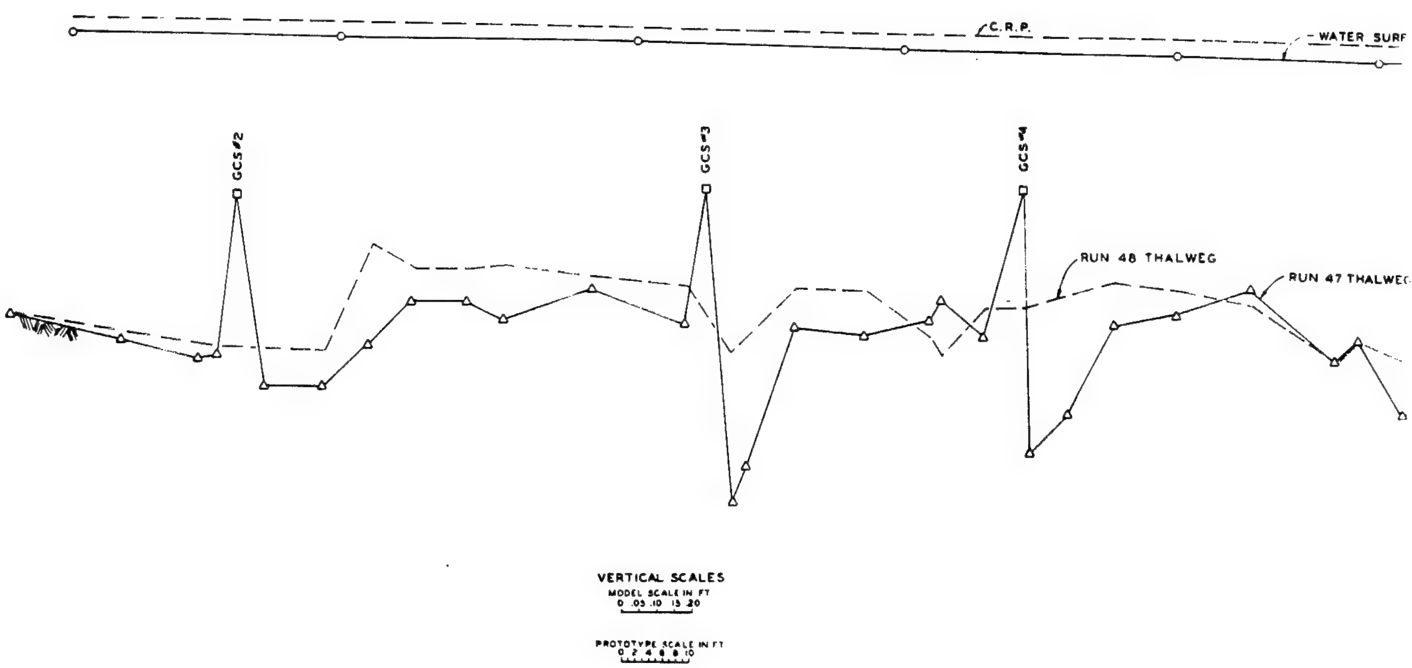
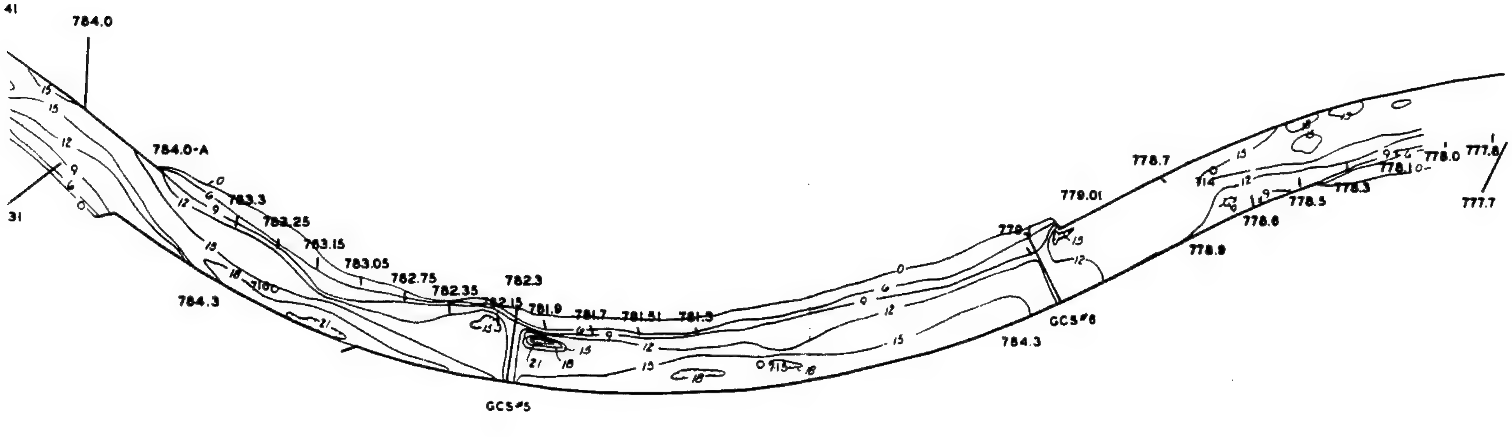
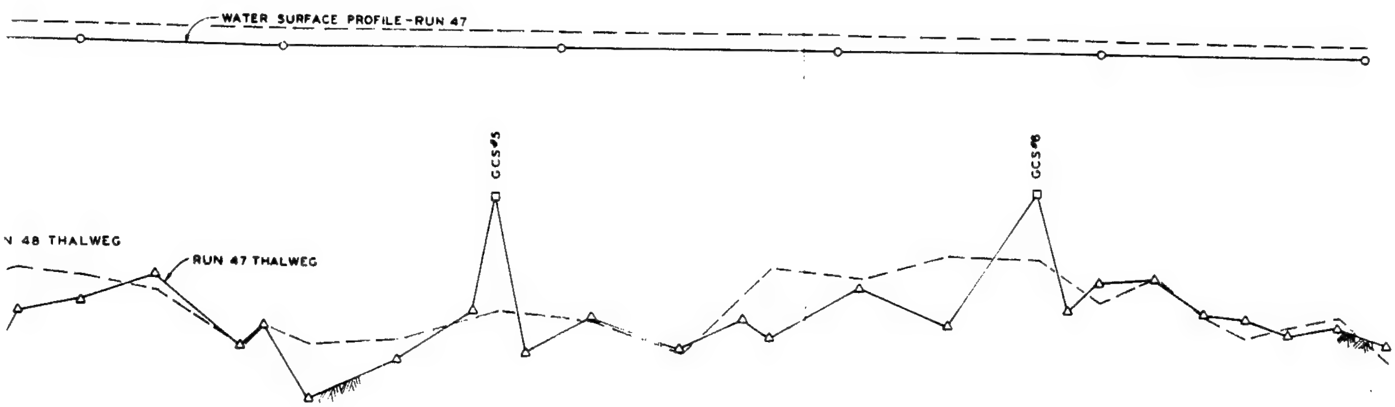
MODEL SCALE IN FT
PROTOTYPE SCALE IN 100 FT.


C.R.P.
WATER SURF
GCS#2
GCS#3
GCS#4
RUN 48 THALWEG
RUN 47 THALWE
VERTICAL SCALES
MODEL SCALE IN FT
PROTOTYPE SCALE IN FT





NOTES:

1. Channel width = 600'.
2. 7 grade control sills at 1 mile intervals with 3 end sills removed and no crossing structures.
3. Discharge = 30,000 cfs with sediment recirculation.

THIS DRAWING HAS BEEN REDUCED TO THREE-EIGHTHS THE ORIGINAL SCALE.

MEAD HYDRAULIC LABORATORY

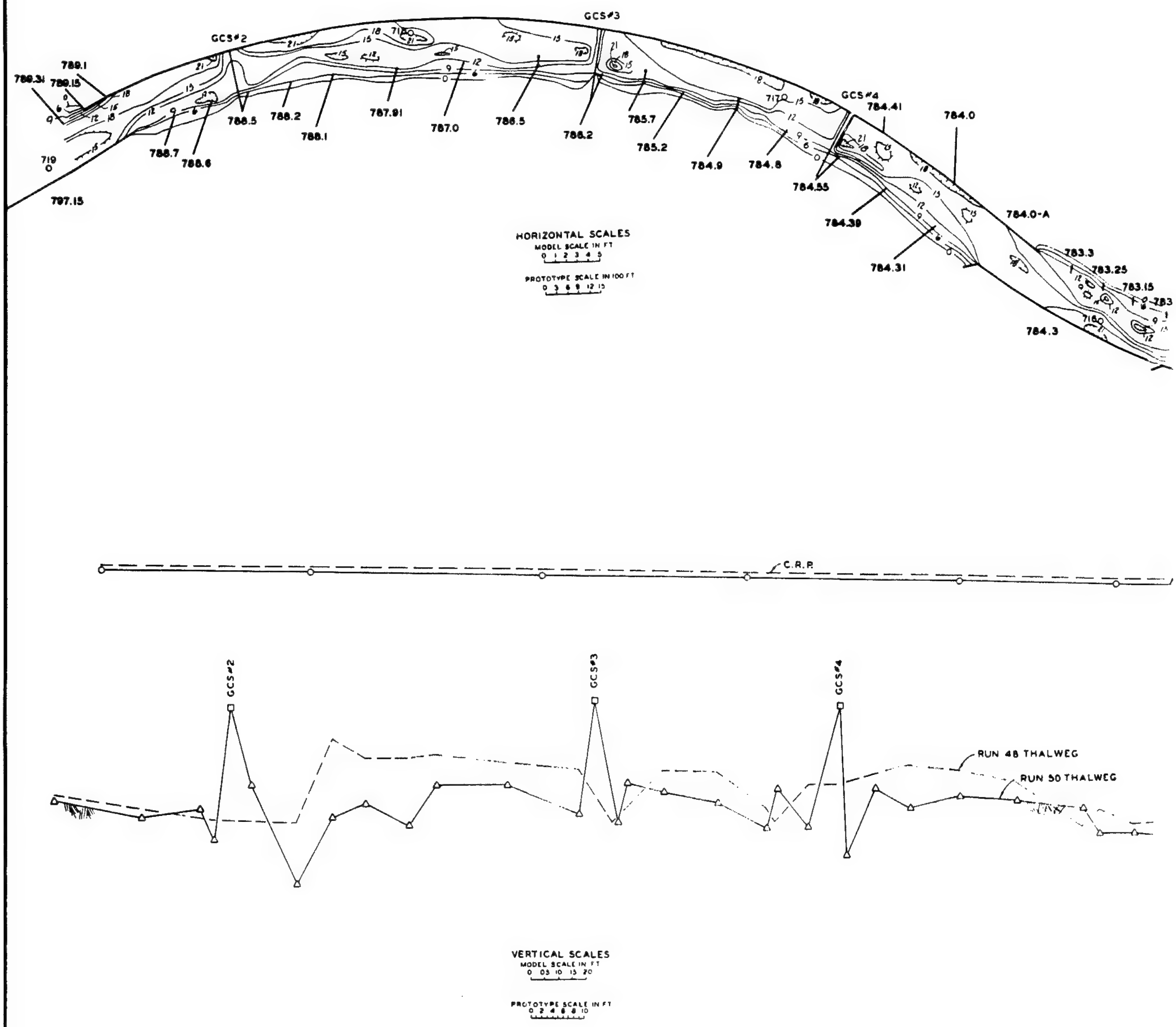
DEGRADATION STUDY

RUN 47

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

PLATE 8

U.S. GOVERNMENT PRINTING OFFICE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797.15
HORIZONTAL SCALES
MODEL SCALE IN FT
0 1 2 3 4 5
PROTOTYPE SCALE IN 100 FT
0 3 6 9 12 15
C.R.P.
RUN 48 THALWEG
RUN 50 THALWEG
VERTICAL SCALES
MODEL SCALE IN FT
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PROTOTYPE SCALE IN FT
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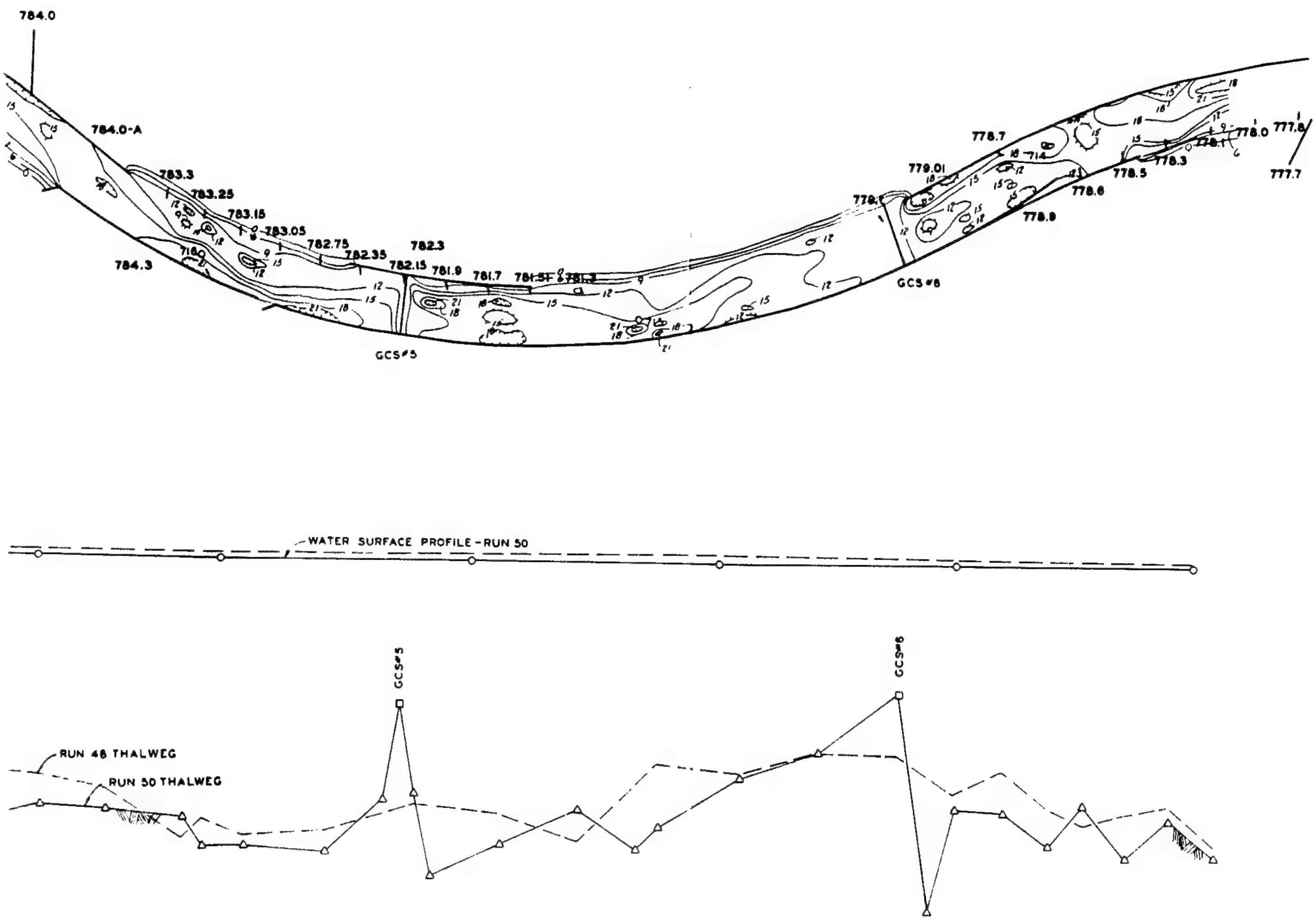
1



NOTES:

1. Channel width = 600'
2. 7 Grade control sills at 1 mile intervals.
3. Discharge = 30,000 cfs with sediment recirculation.

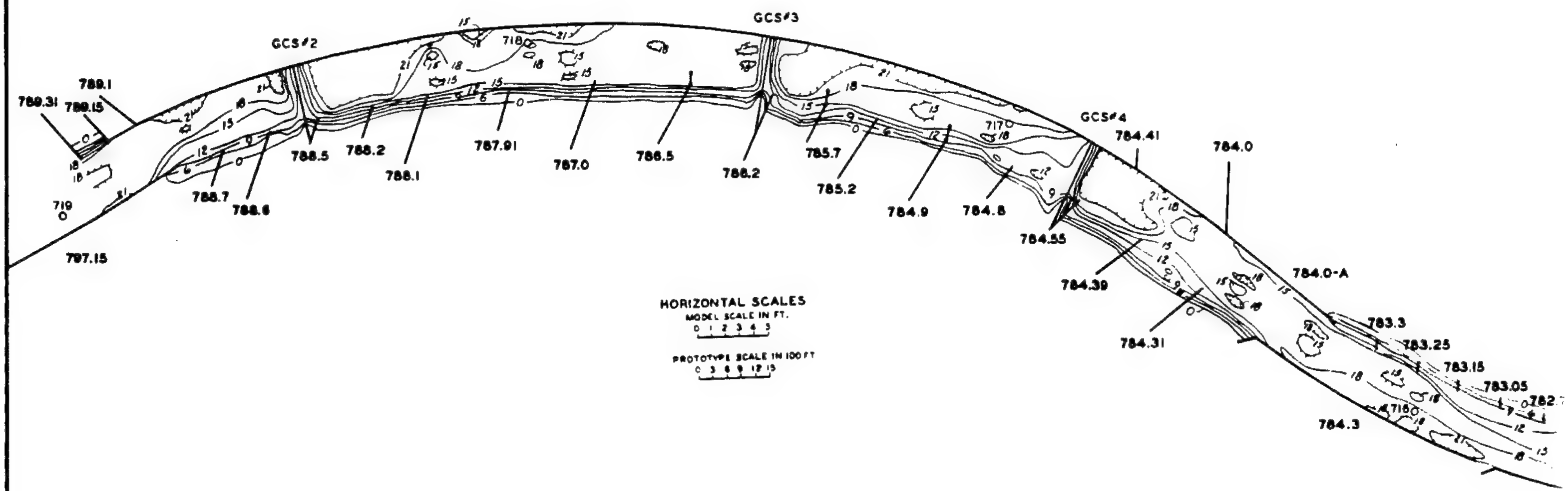
MEAD HYDRAULIC LABORATORY

DEGRADATION STUDY

RUN 50

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

2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784.41
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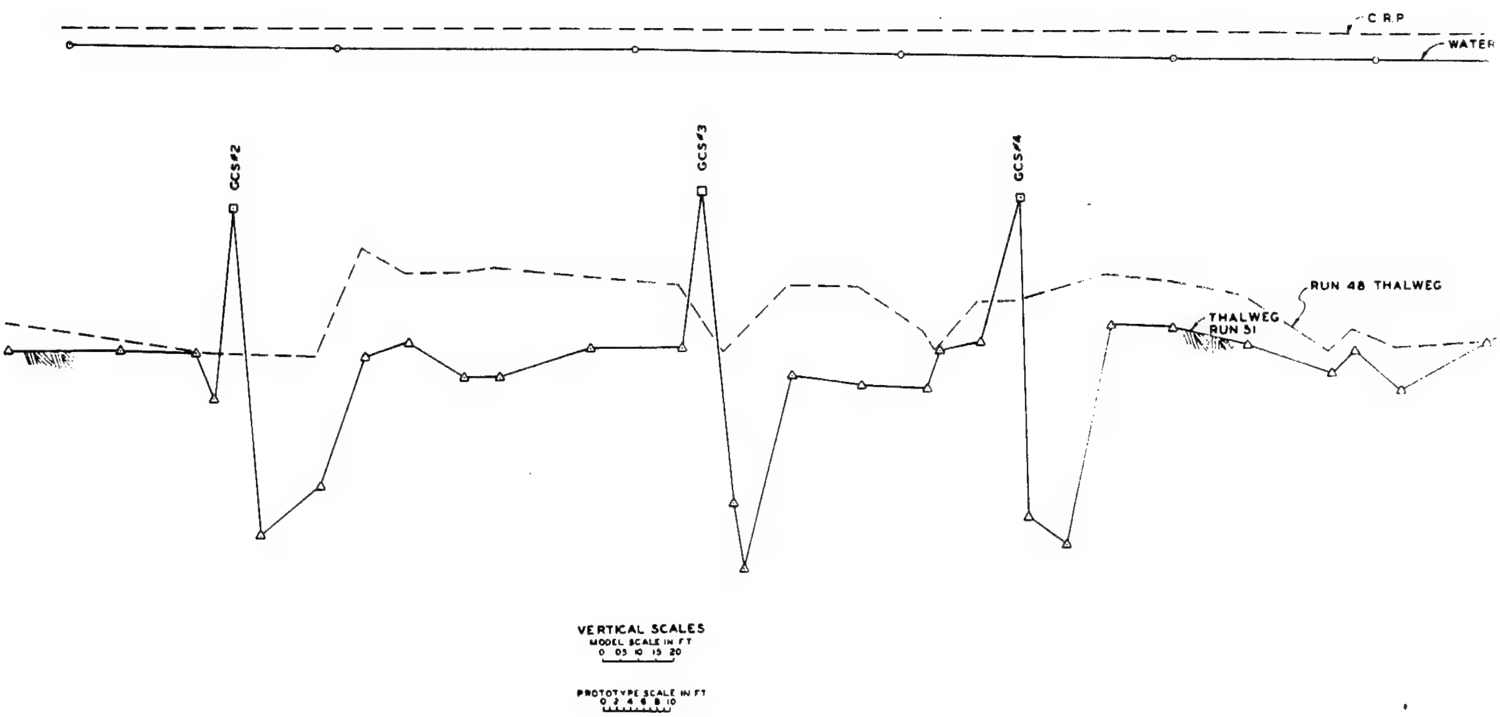
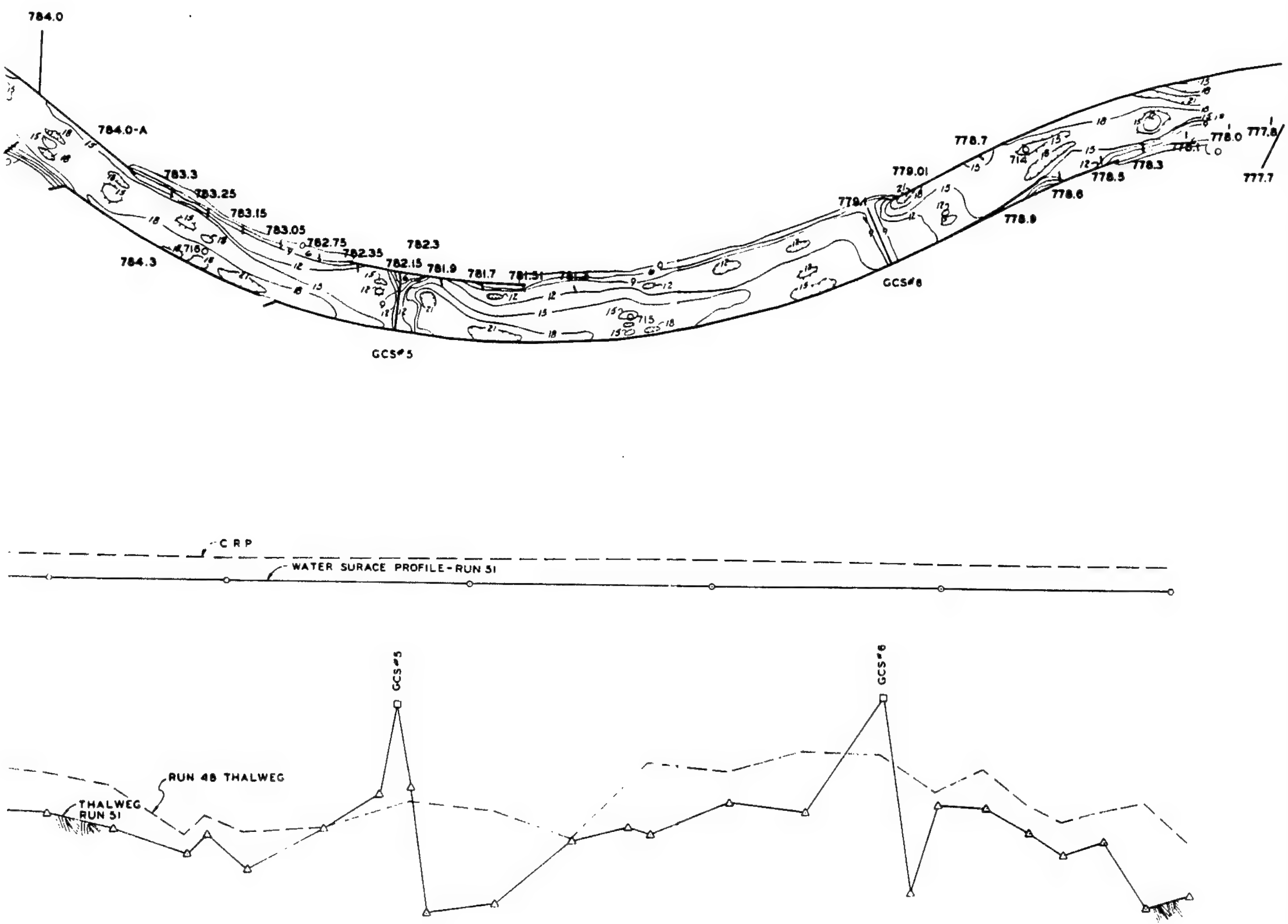
HORIZONTAL SCALES
MODEL SCALE IN FT.
0 1 2 3 4 5
PROTOTYPE SCALE IN 100 FT
0 3 6 9 12 15


C.R.P.
WATER
GCS#2
GCS#3
GCS#4
RUN 48 THALWEG
THALWEG
RUN 51
VERTICAL SCALES
MODEL SCALE IN FT
0 .05 .10 .15 .20
PROTOTYPE SCALE IN FT
0 2 4 6 8 10

1



NOTES:

1. Channel width = 600'
2. 7 Grade control sills at 1 mile intervals.
3. Discharge = 30,000 cfs "starvation test"

THIS DRAWING HAS BEEN REDUCED TO THREE-EIGHTHS THE ORIGINAL SCALE

MEAD HYDRAULIC LABORATORY

DEGRADATION STUDY

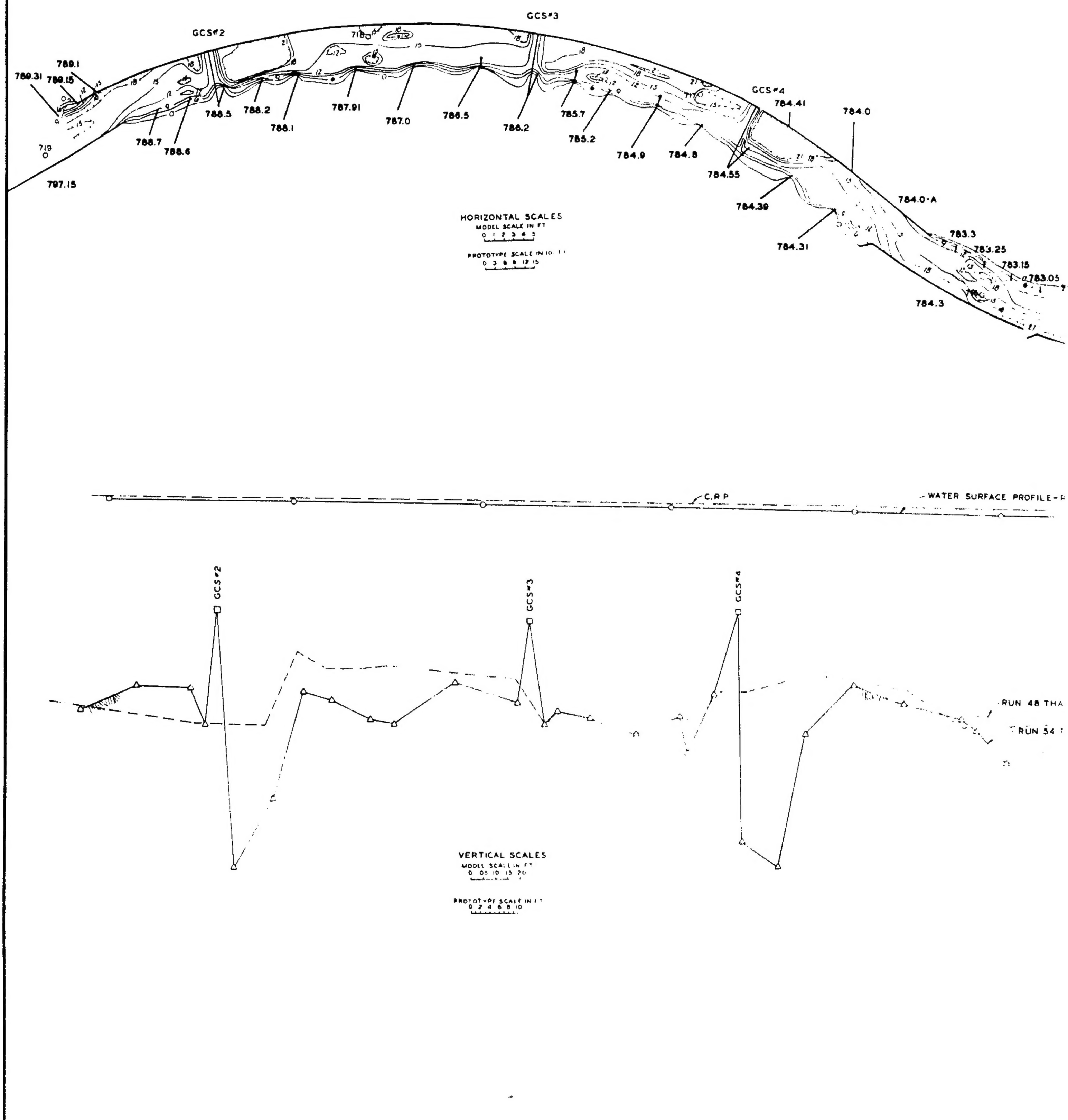
RUN 51

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

2

PLATE 10

U.S. GOVERNMENT PRINTING OFFICE



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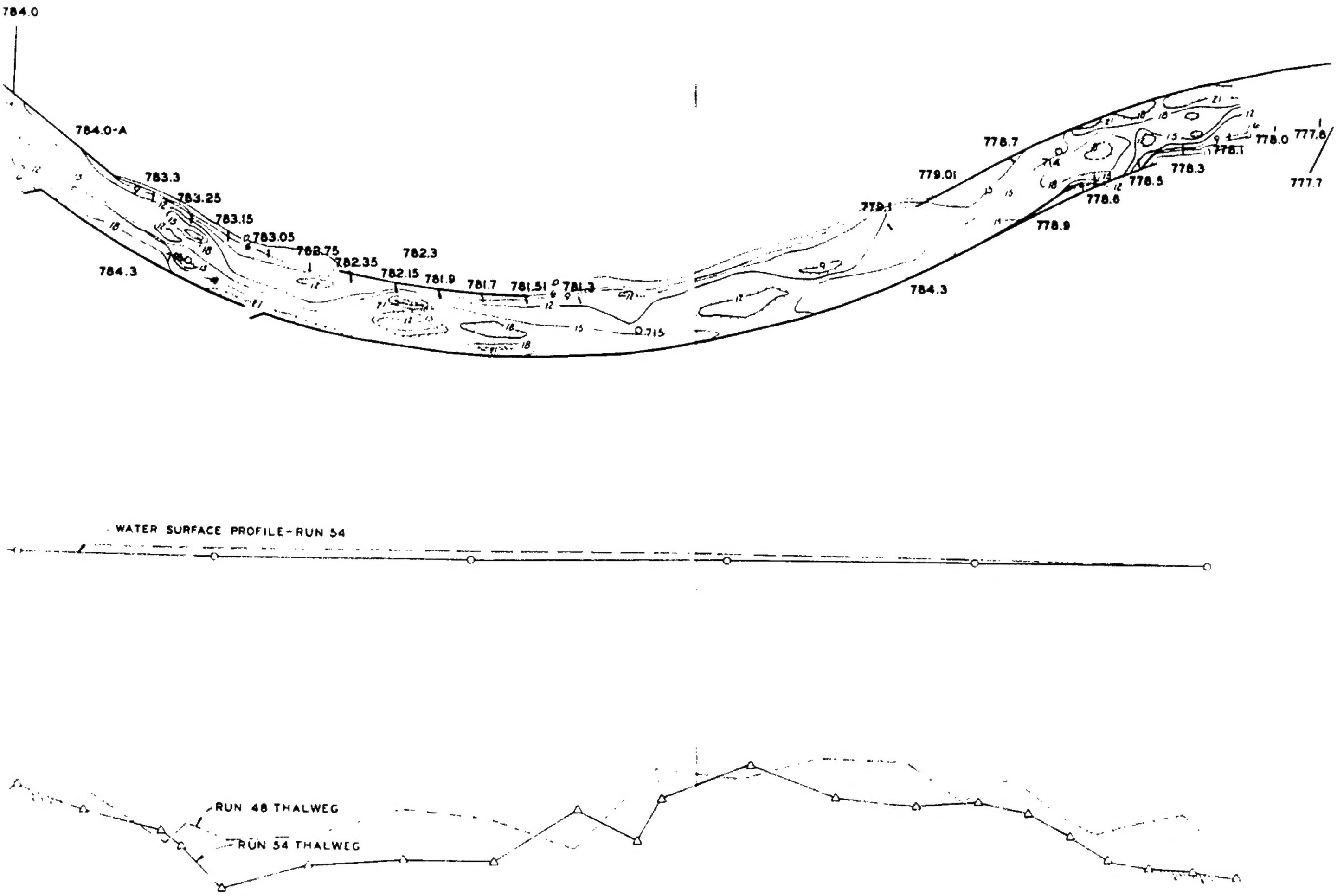
784.9
784.8
784.55
784.41
784.39
784.31
784.0
784.0-A
783.3
783.25
783.15
783.05
784.3
797.15
719
718
HORIZONTAL SCALES
MODEL SCALE IN FT
0 1 2 3 4 5
PROTOTYPE SCALE IN 100 FT
0 3 6 9 12 15
C.R.P
WATER SURFACE PROFILE
RUN 48 THA
RUN 54
VERTICAL SCALES
MODEL SCALE IN FT
0 .05 .10 .15 .20
PROTOTYPE SCALE IN FT
0 2 4 6 8 10

1



NOTES:

1. Channel width= 600'
2. 4 Grade control sills in the upper half of model.
3. Discharge = 30,000 cfs with sediment recirculation.

MEAD HYDRAULIC LABORATORY

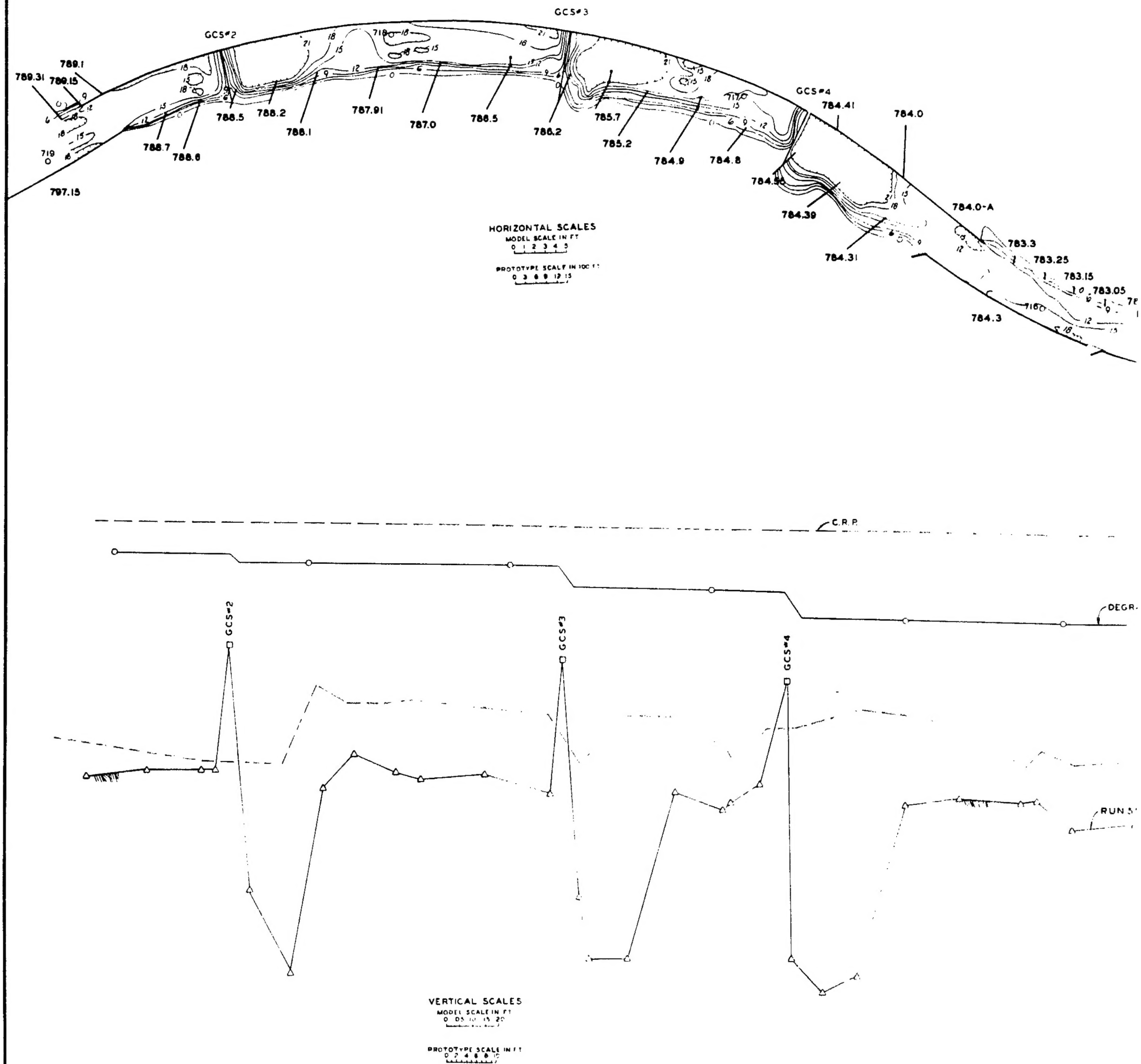
DEGRADATION STUDY

RUN 54

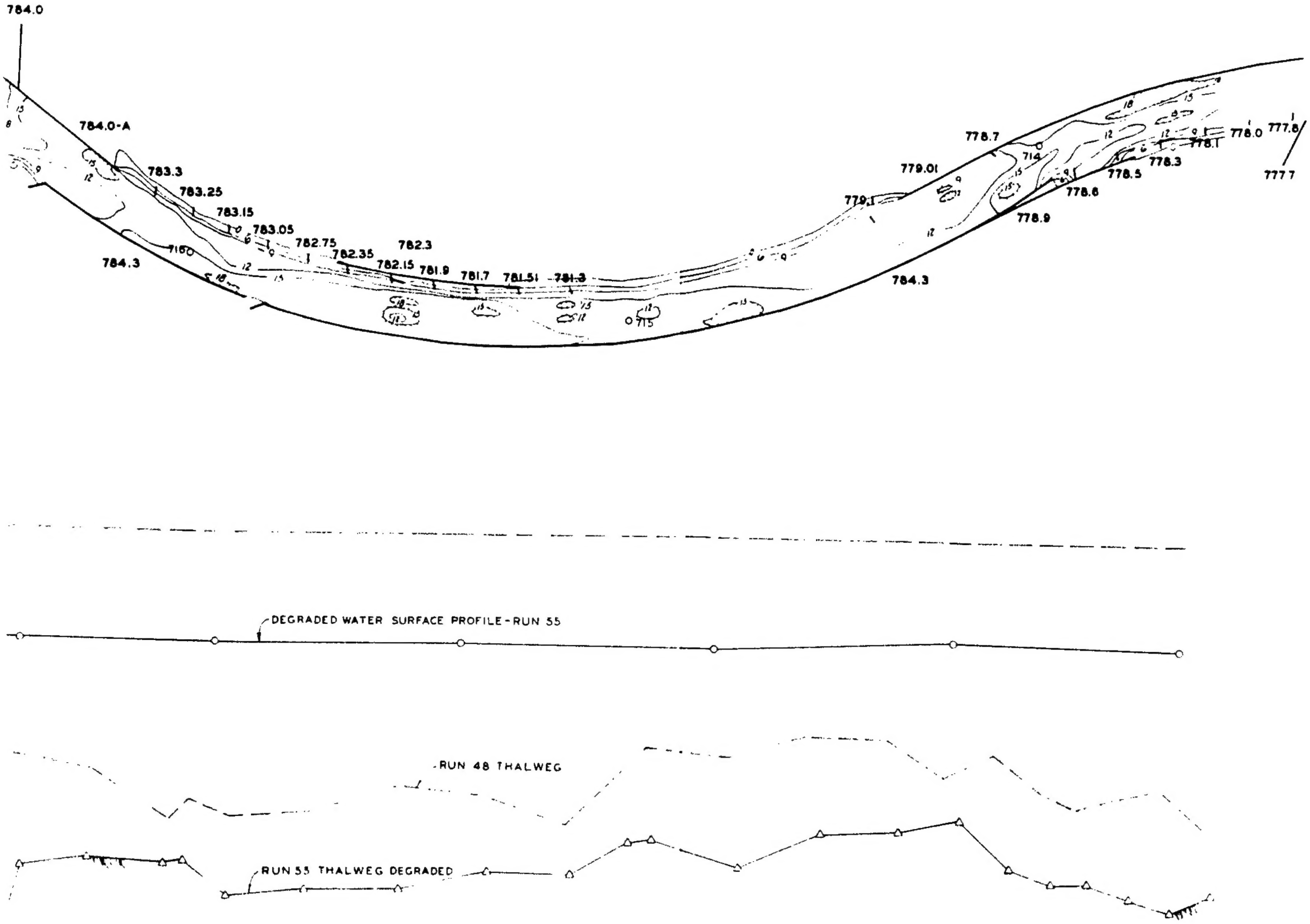
U. S. ARMY ENGINEER DISTRICT, OMAHA

CORPS OF ENGINEERS OMAHA, NEBRASKA

2


GCS#2
GCS#3
GCS#4
789.1
789.31
789.15
719
797.15
788.7
788.6
788.5
788.2
788.1
787.91
787.0
786.5
786.2
785.7
785.2
784.9
784.8
784.41
784.0
784.39
784.31
784.0-A
783.3
783.25
783.15
783.05
784.3
HORIZONTAL SCALES
MODEL SCALE IN FT
0 1 2 3 4 5
PROTOTYPE SCALE IN 100 FT
0 3 6 9 12 15
C.R.P.
DEGR.
GCS#2
GCS#3
GCS#4
RUN
VERTICAL SCALES
MODEL SCALE IN FT
PROTOTYPE SCALE IN FT

1



NOTES:

1. Channel width = 600'
2. 4 Grade control sills in the upper half of model.
3. Discharge 30,000 cfs

MEAD HYDRAULIC LABORATORY

DEGRADATION STUDY

RUN 55

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA

2

PLATE 12